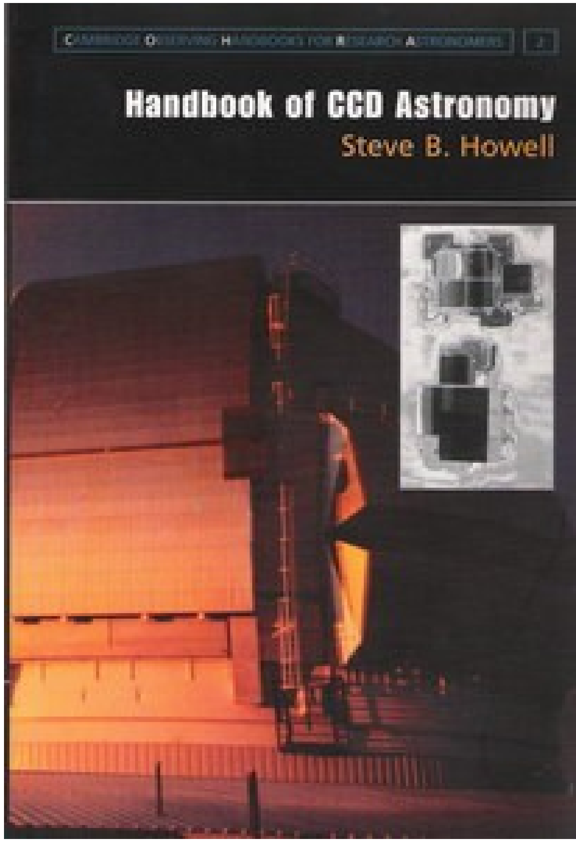
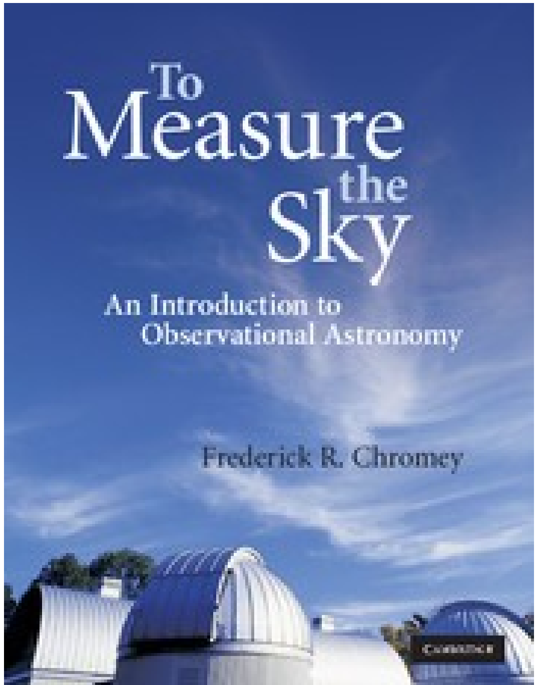
AGA5802
CCDs, data reduction, noise

- *To Measure the Sky*
- *Handbook of CCD astronomy*
- *Introduction to CCDs:*

astro.kent.ac.uk/~df/teaching/ph507/tel_4.pdf



Prof. Jorge Meléndez



CCDs: size$

- Typically (old: 256x256, 512x512 pixels), 1024 x 1024, 2048x2048, 4096 x 4096

Pixels of ~10 – 20 μm

- One of the largest is CCD231-C6 da E2V:

6144 x 6144 pixels

The pixels are 15μm in size

Total size: 92.16 mm x 92.40 mm

CCD Heritage : Large Area Thinned

Teledyne e2v

We have extensive experience in the design and manufacture of large area back illuminated CCDS :

CCD 42-90 :	13.5µm pixel,	2k x 4.5k	: General astronomy	>400 of these two types supplied
CCD44-82 :	15µm pixel,	2k x 4k	: General astronomy	

CCD43-62 :	15µm pixel,	4k x 2k	: Hubble WFC3 + ACS flight spares
CCD74-50 :	12µm pixel,	2k x 4k	: Solar B/SOT/FPP/ Filtergraph.
CCD42-CO :	13.5µm pixel,	2k x 6k	: Eddington
CCD90-52 :	27µm pixel,	2200 x 1044	: Kepler
CCD91-72 :	30µm x 10µm pixel,	1966 x 4500	: GAIA ASTRO AF
CCD203-82 :	12µm pixel	4k x 4k	: SDO : HMI / AIA & LAMOST
CCD231-84 :	15µm pixel	4k x 4k	: General astronomy

And now the very large area

CCD231- 68 :	15µm pixel	8k x 3k	LBT **M**ulti-**O**bject **D**ouble **S**pectrograph
CCD231- C6 :	15µm pixel	6k x 6k	Next generation astronomy imager
CCD290- 99 :	10µm pixel	9k x 9k	Next generation astronomy imager

Discovery Channel Telescope

http://www.lowell.edu/techSpecs/LMI/LMI.html

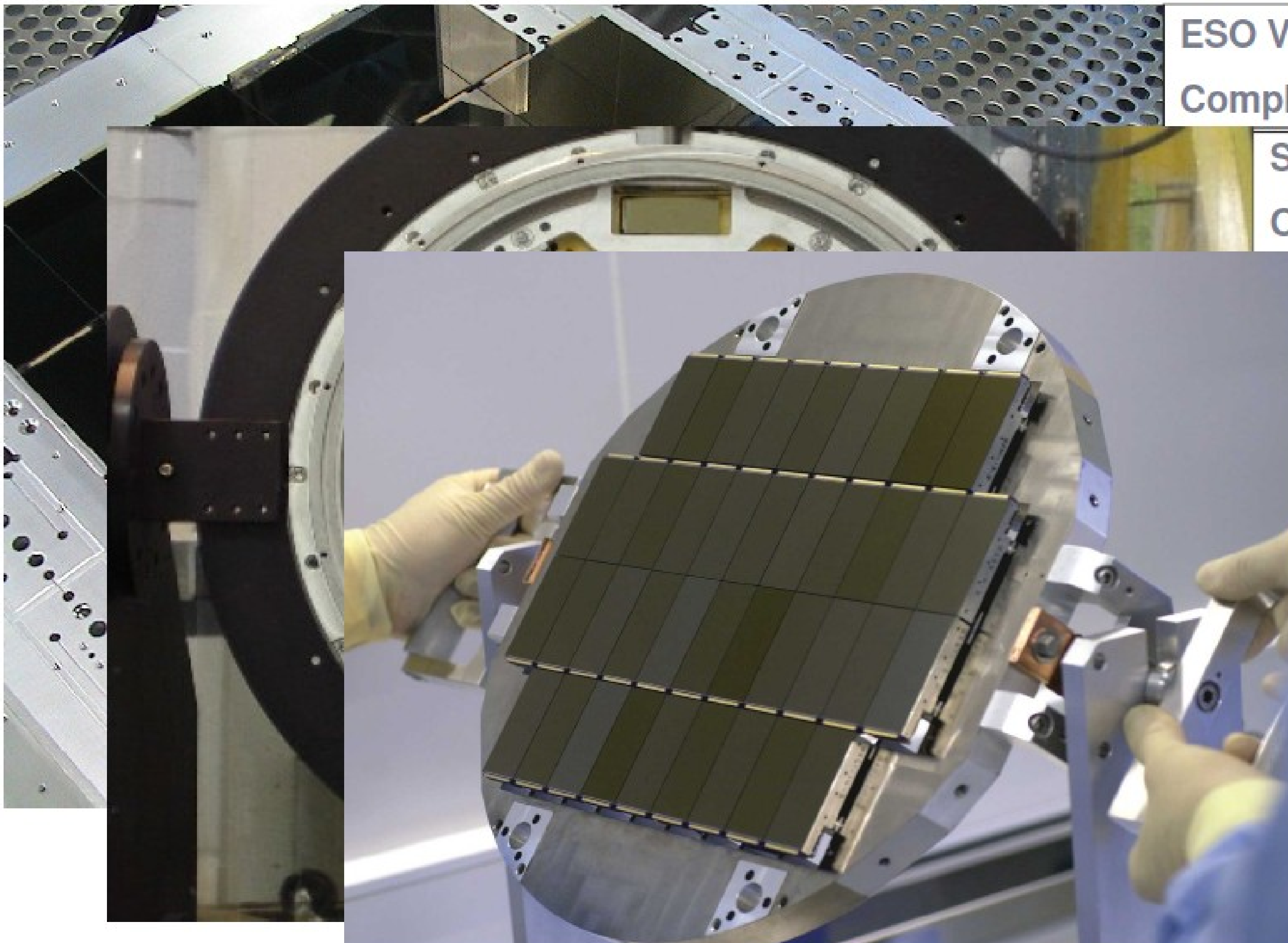
LMI (Large Monolithic Imager) of Discovery Channel Telescope (4,3m) at Lowell Observatory

NGC 891 is an edge-on spiral galaxy, located about 10 Mpc (32 million light-years) away. The exposure was unguided and consist of ten 1-min exposures in B, five 1-minute exposures in V, and six 1-minute exposures in R. This was the ``first-light" image obtained with LMI obtained on September 12, 2012. **The field of view shown is 11.7 arcminutes on a side.**

Total field of view of CCD is about 13’ x 13’

Ground-based CCD mosaic
CCD44-82 & CCD42-90

Teledyne e2v



ESO VST Omegacam

Completed in lab.- 2005

SAO MMT Megacam

On telescope- 2005

CFHT Megacam

Operational- April 2003

Kepler planet hunter

Teledyne e2v

Image supplied courtesy of Ball Aerospace

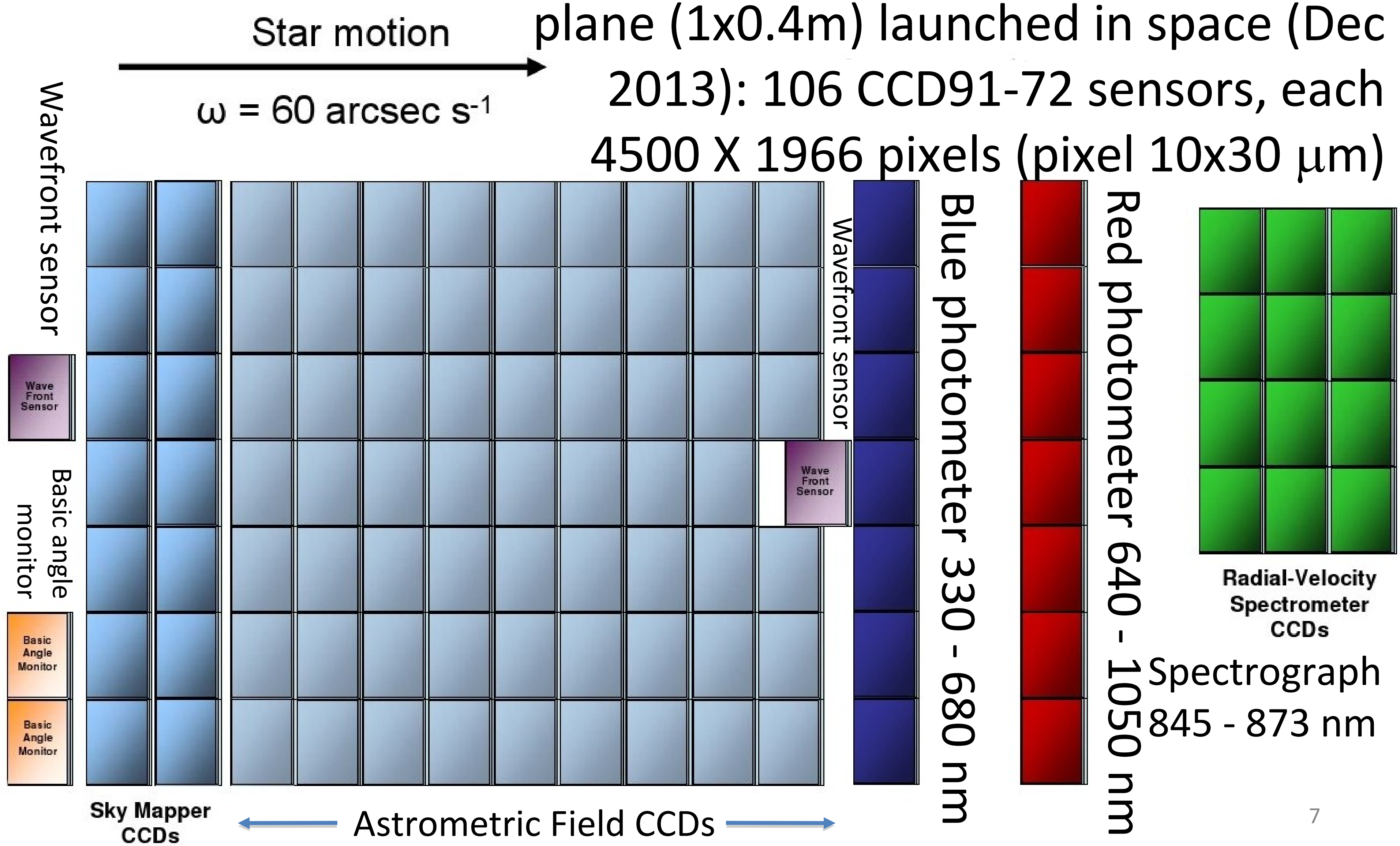
e2v supplied the CCDs for the Kepler instrument, which will greatly extend the search for extra-terrestrial planets

Mosaic of 42 1024x2048 CCDs

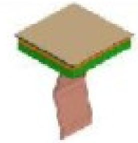
FOV about 12^{o} diameter, but each pixel has ~ 4 arcsec

GAIA: 106 CCDs from Teledyne e2V

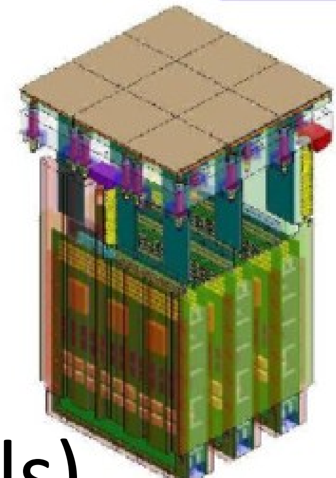
ESA's GAIA mission had the largest focal plane (1x0.4m) launched in space (Dec 2013): 106 CCD91-72 sensors, each 4500 X 1966 pixels (pixel 10x30 μm)



LSST: Large Synoptic Survey Telescope, 2023?
Vera Rubin



4K x 4K pixels on 10μm centers
16 readouts/sensor
330 nm to 1070 nm response
1 second read time



9 CCD's assembled
into one raft
21 rafts in the camera

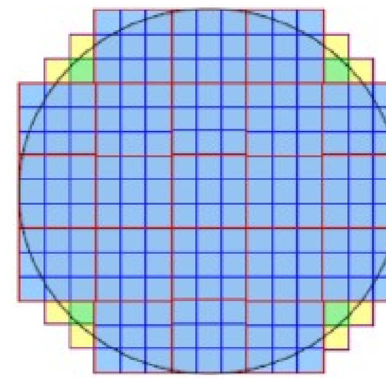
189 CCDs (4096x4097 pixels)

FOV 3.5° diameter

Acknowledgements to LSST

From AAS Jan 2008

The 63cm diameter
focal plane has 189
CCD's arranged on 21
modular rafts



© e2v

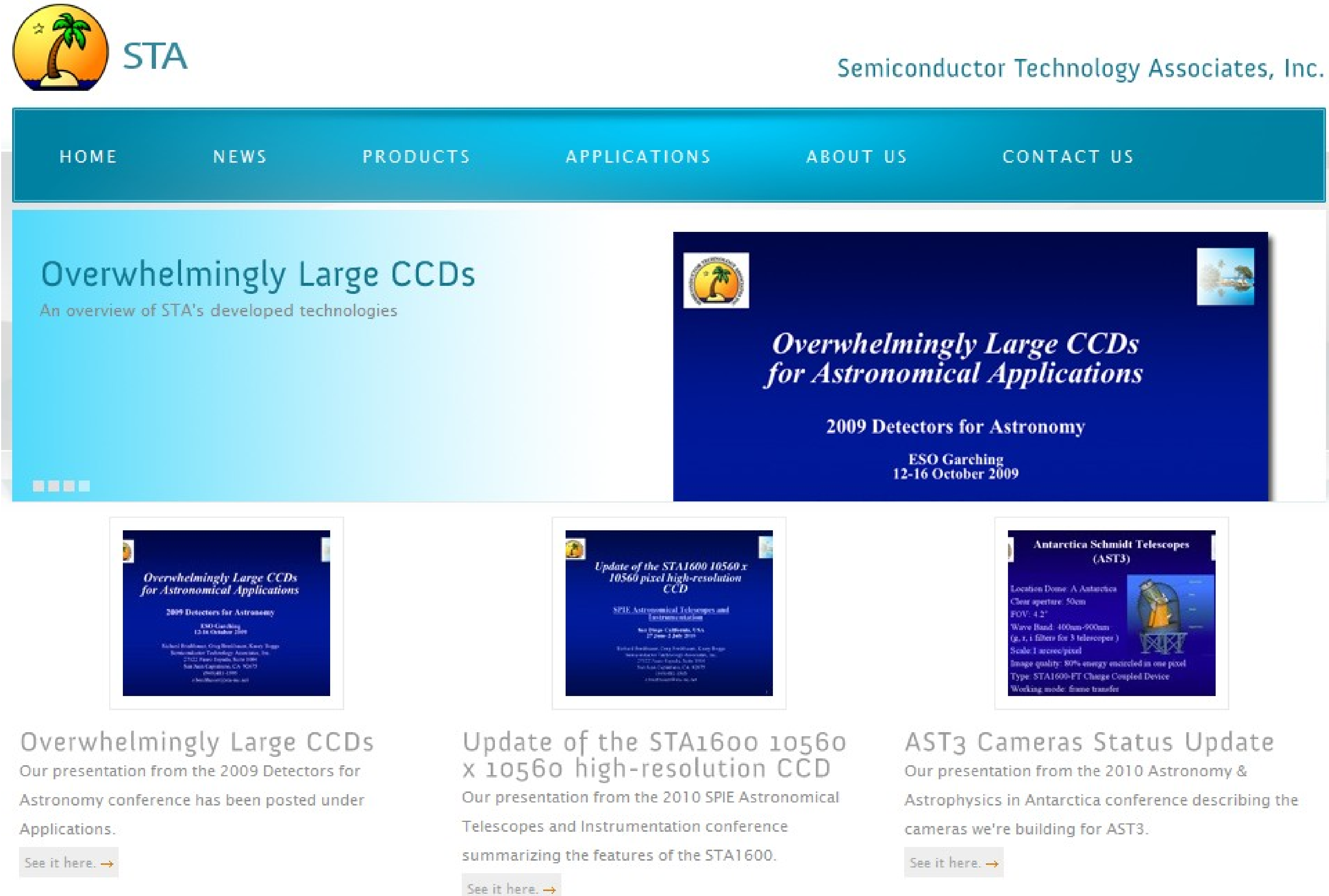
8-m telescope

6-band (0.3-1.1 micron) wide-field deep astronomical survey of over 20,000 square degrees. Each patch of sky will be visited about 1000 times in ten years.

3200 Megapixels -- 9.6 square degree field of view -- 30 terabytes per night

STA also produces huge chips

http://www.sta-inc.net/



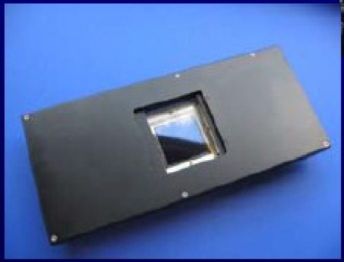
STA1600

http://www.sta-inc.net/product-1/

- 10560 x 10560
- 9 um pixel CCD
- 95.2 × 95.1 mm

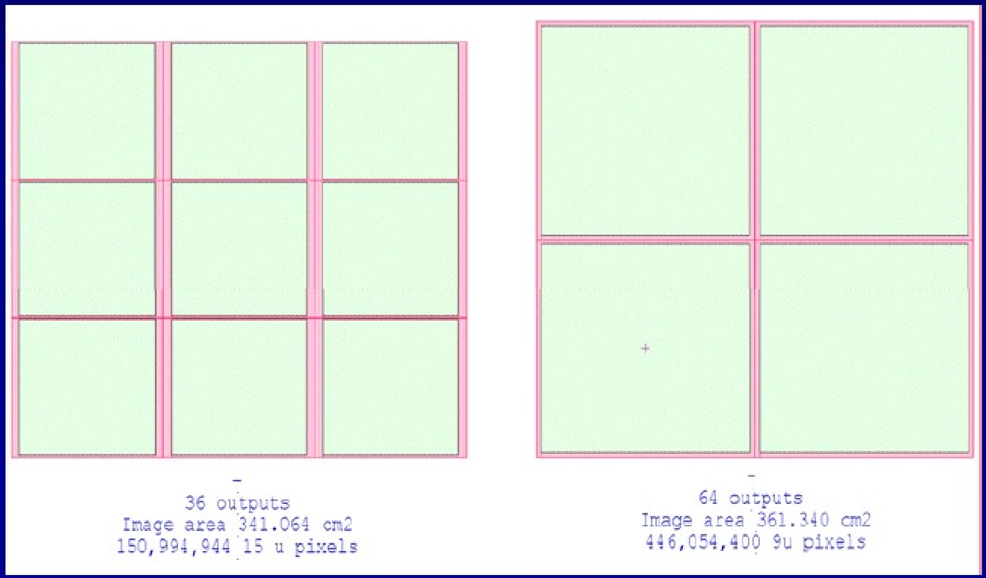
USNO Robotic Astrometric Telescope URAT

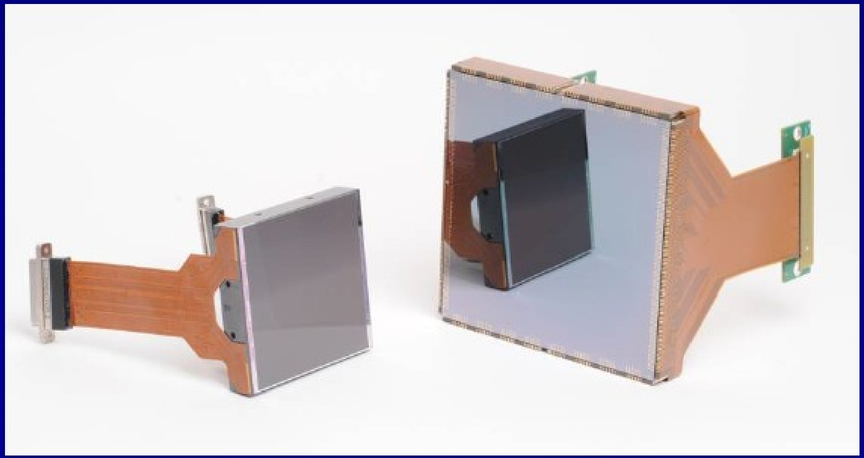
- 8 inch Refracting Telescope for Astrometry
- Upgrade initiated to a 2x2 array by Dr Norbert Zacharias for an all sky survey - URAT
- STA is providing complete system including
  - Dewar – Window – Bonn Shutter
  - Four BI STA1600B CCDs – Three STA 3000 Guiders
  - Five Aura cameras with software
  - Telescope robotic control software



http://www.sta-inc.net/wp-content/uploads/2010/08/Overwhelmingly-Large-CCDs-for-Astronomy.pdf

Large Focal Plane Efficiency





E2V CCD231 adjacent to STA1600

- Four 10ks provide more active image area than nine 4k imagers
- 91% Active area for 4k imager
- 95% Active area for 10k imager

http://www.sta-inc.net/wp-content/uploads/2010/08/Overwhelmingly-Large-CCDs-for-Astronomy.pdf

CCD reading

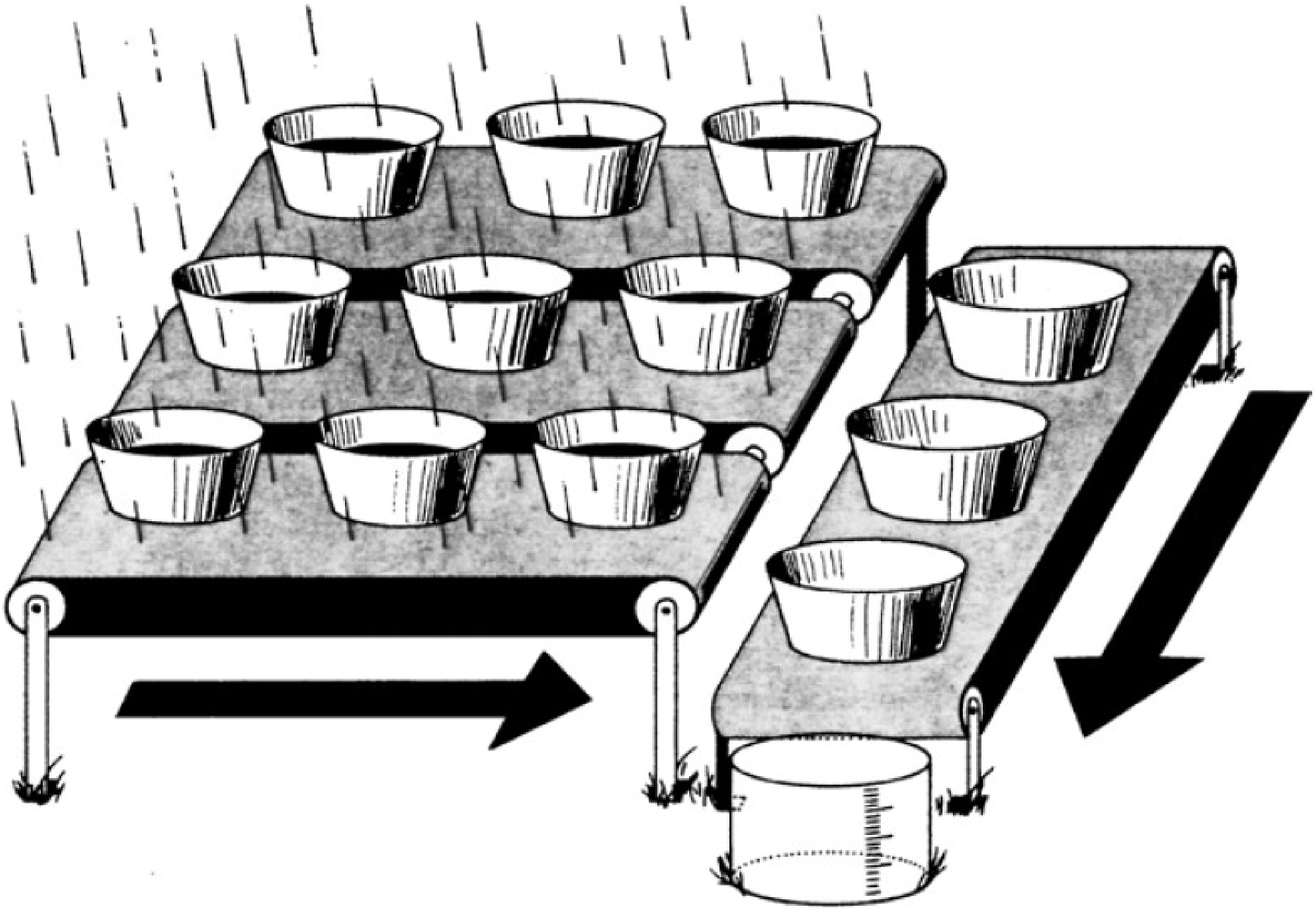
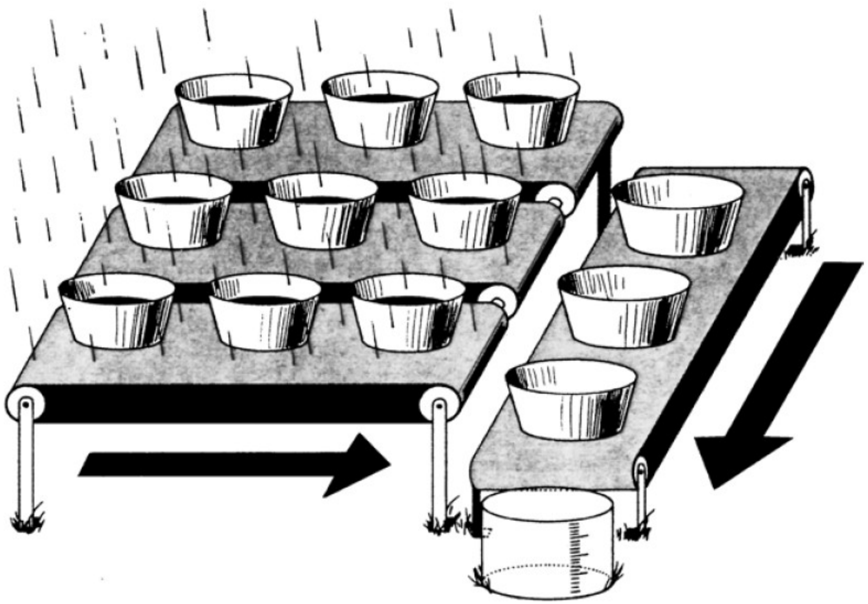


Fig. 2.1. CCDs can be likened to an array of buckets that are placed in a field and collect water during a rainstorm. After the storm, each bucket is moved along conveyor belts until it reaches a metering station. The water collected in each field bucket is then emptied into the metering bucket within which it can be measured. From Janesick & Blouke (1987).

Transfer efficiency

- Early values about 0,999 (99,9%).

For 200 transfers (100x100 array) :



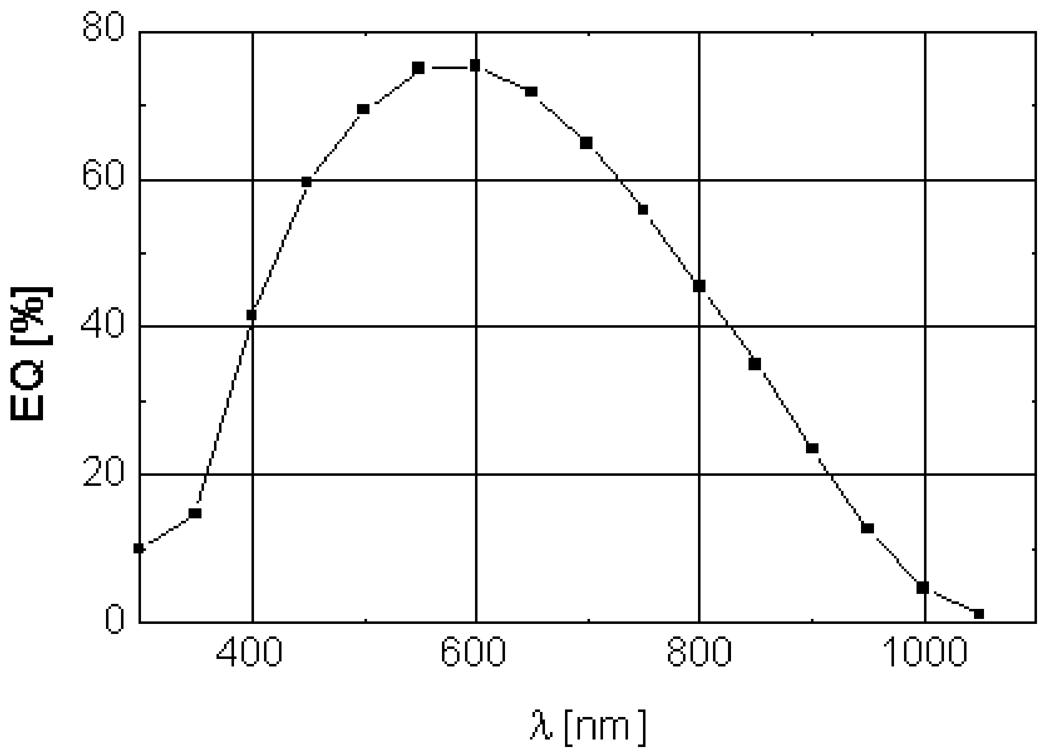
$$100 \text{ x } 0.999^{200} = 81\%$$

- Modern values (year 2000), charge transfer efficiency ~ 0,999 999

Quantum efficiency (Q.E.)

$$Q.E. = \frac{\text{number of detected photons}}{\text{number of incident photons}}$$

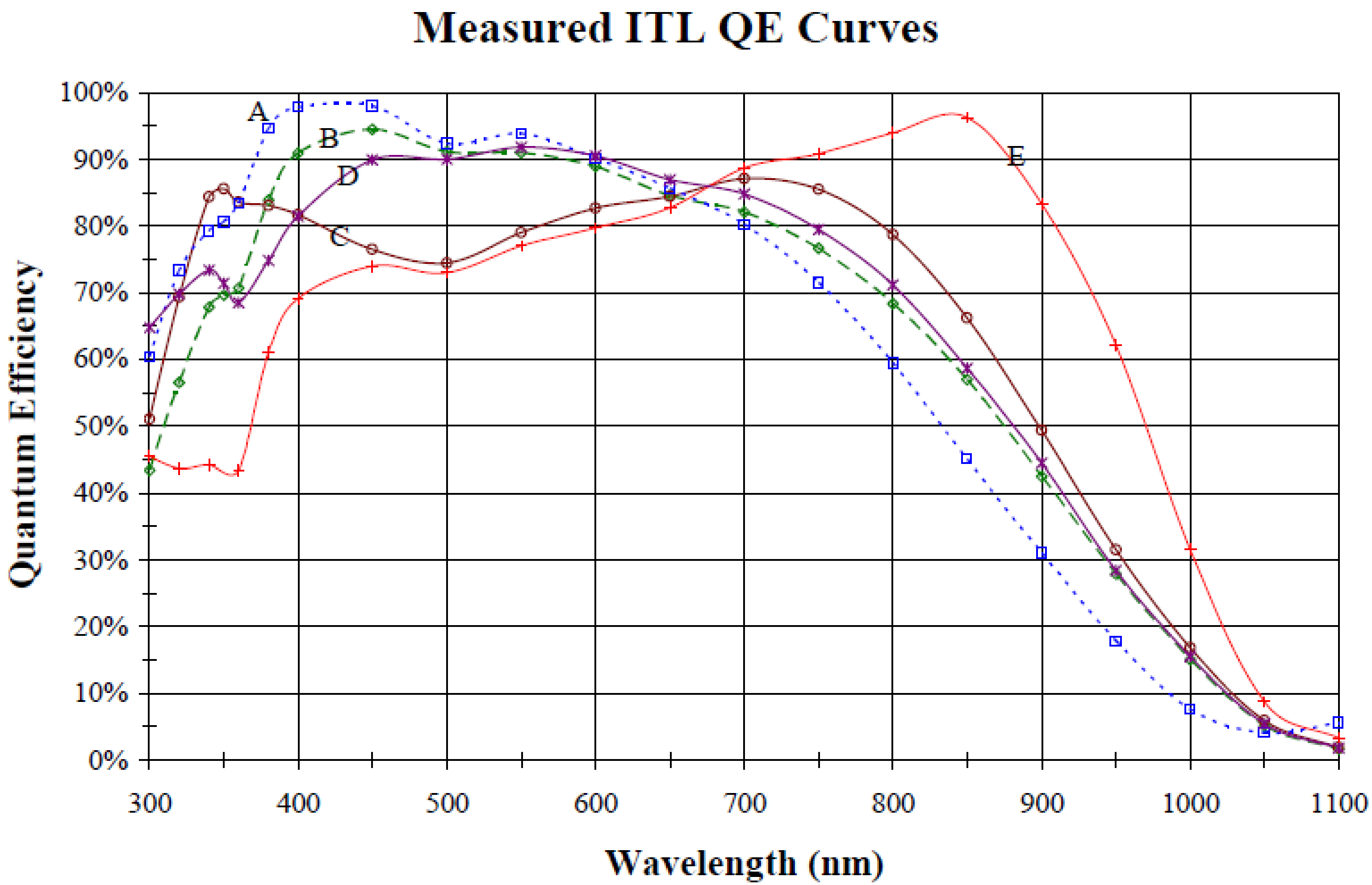
Quantum efficiency - CCD 105 (OPD)



http://www.lna.br/opd/instrum/ccd/qefull_105_160.html

Quantum efficiency

For STA arrays



M. Lesser, University of Arizona Imaging Technology Laboratory

- A and B are blue optimized coatings.
- C and D are broadband. D is a new AR coating .
- E is a device with a red optimized coating.

http://www.sta-inc.net/wp-content/uploads/2010/08/Overwhelmingly-Large-CCDs-for-Astronomy.pdf

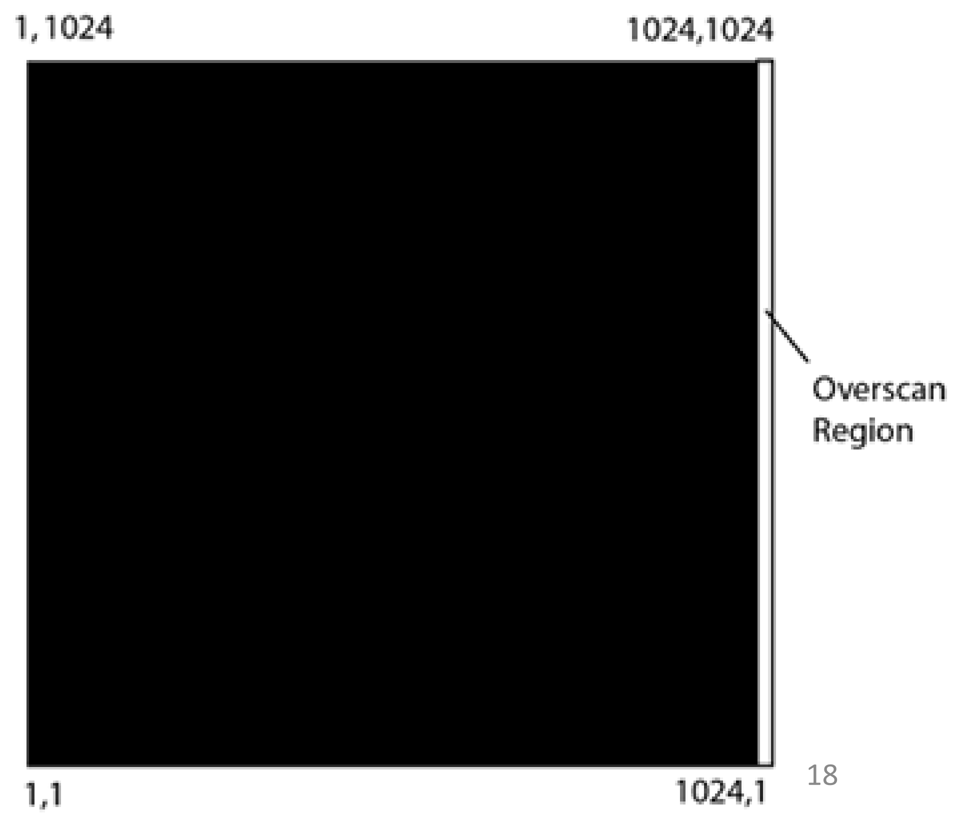
Bias

- A bias frame is an exposure of zero duration taken with the camera shutter closed and all lights off
- “zero point” of reading
- Get at **least** 5-10 bias and combine using the median
- Problem: variations during the observing run?

Bias & overscan

- Mean value of the **bias** could also be obtained from the overscan region of the CCD
- If you forgot to observe bias frames
  → bias = median(overscan)
- If there are changes in the bias, you can use the overscan region to correct for those changes.

Overscan example for a 1024 x 1024 CCD



Flat

Image to correct differences in the sensibility of the CCD. Observe **at least** 5-10 flats.

"dome" flat

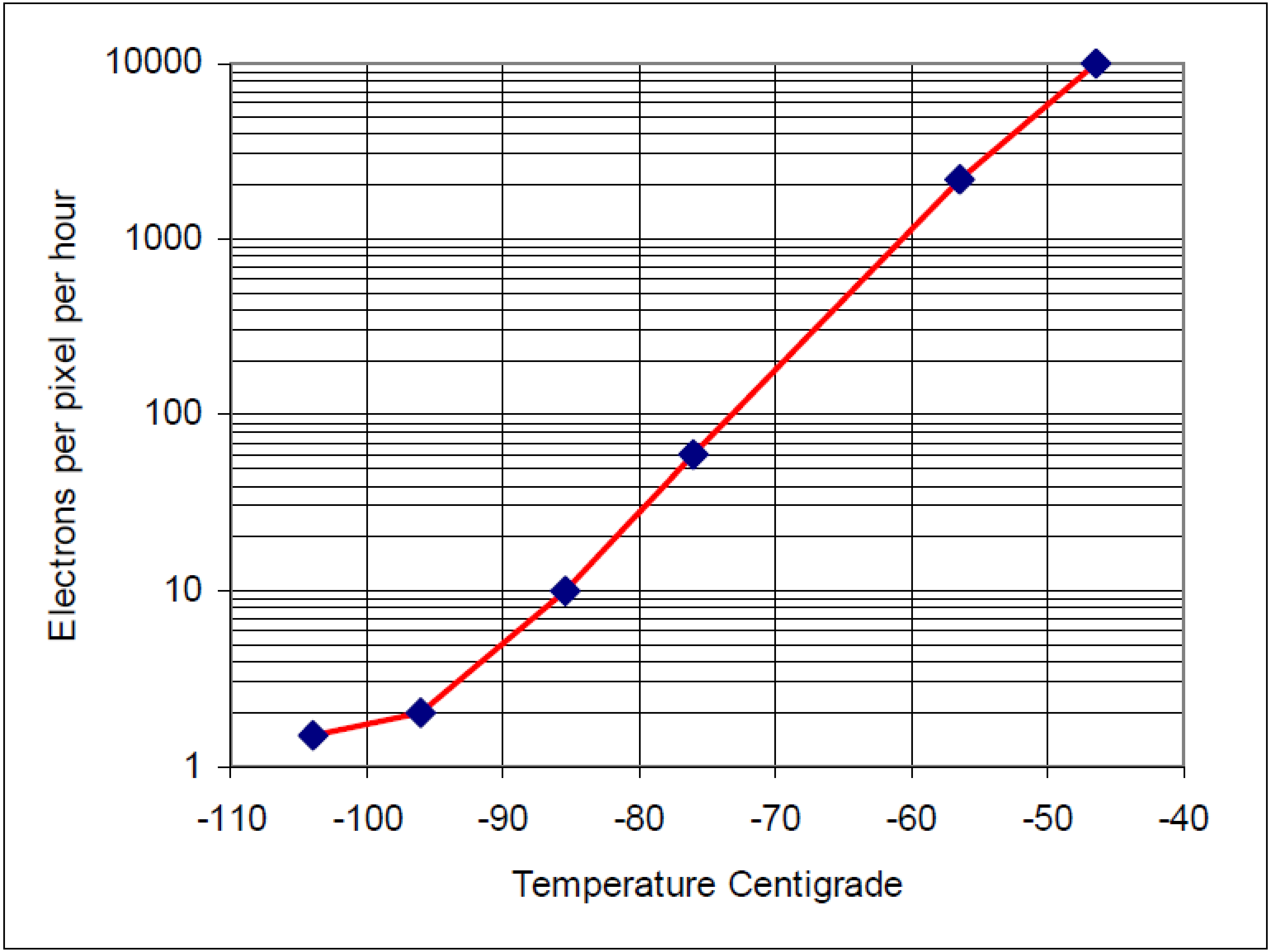
1,6m do OPD
Março 2013

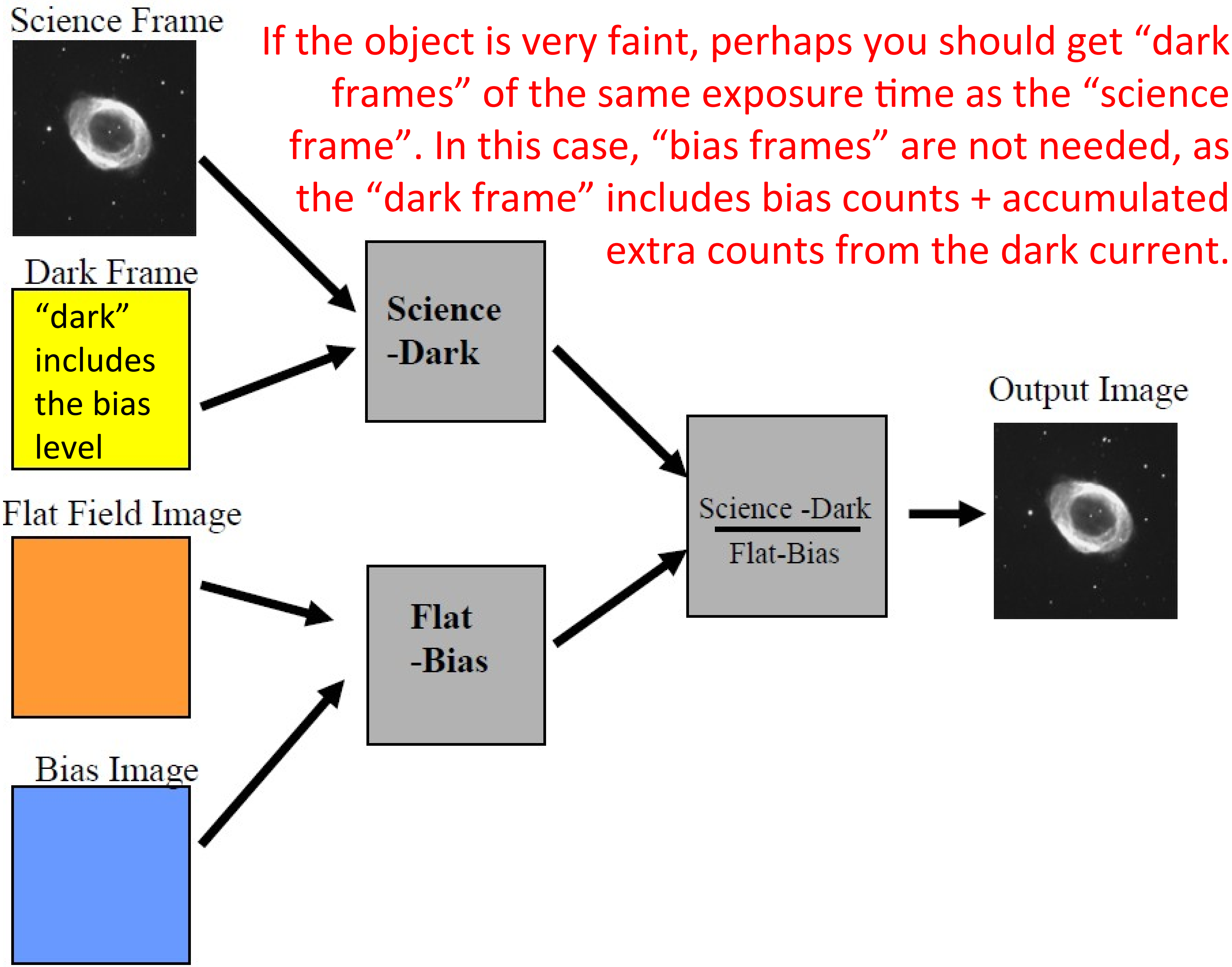
Dark (current)

- Dark current is due to random counts from the thermal effect. Is negligible in cooled CCDs
- Could be important only for very weak objects
- Should be exactly of the same observing time as in your object, or scale with time:

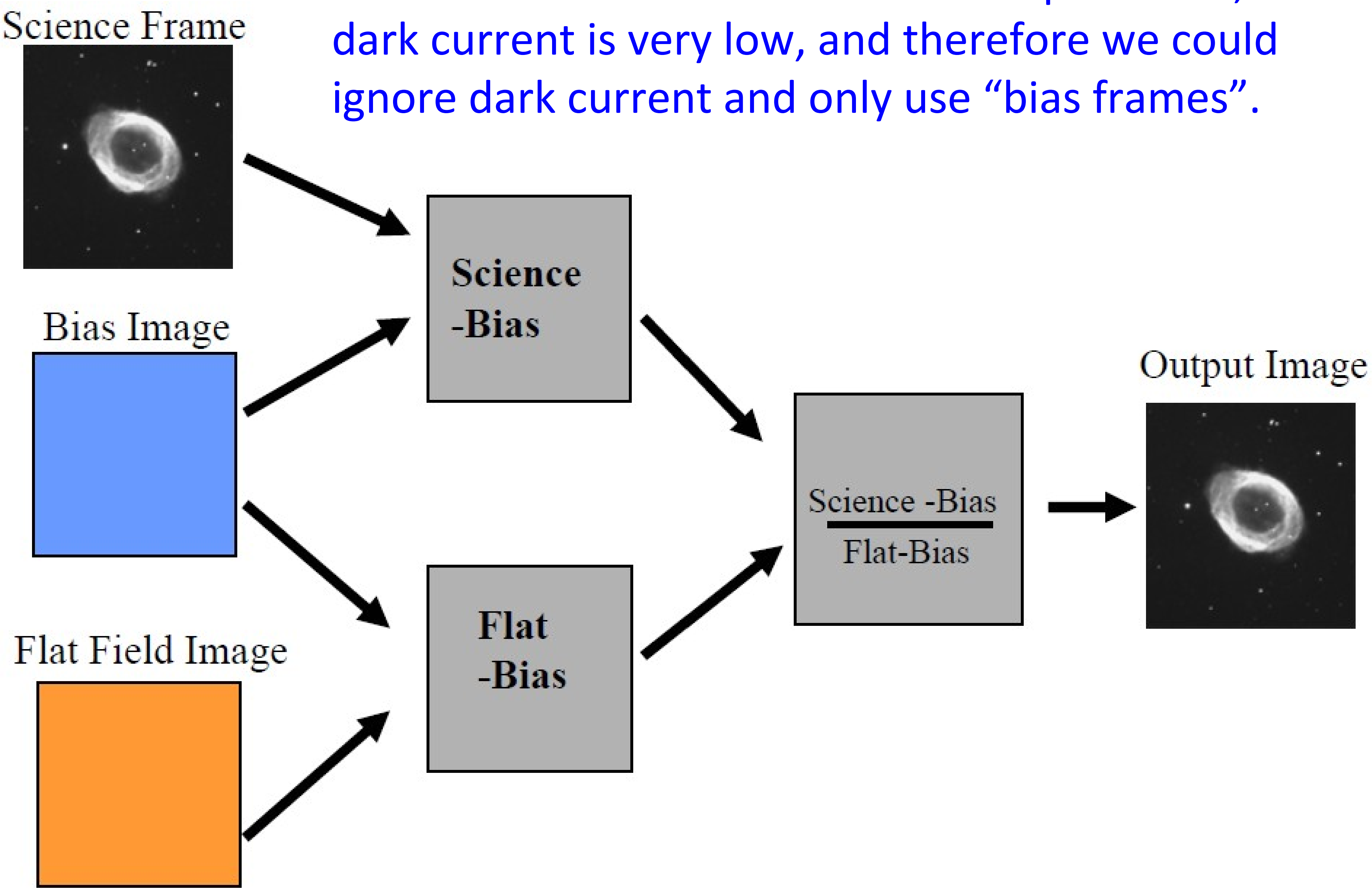
ΔDark/time = (Dark – bias)/time

Dark current of a TEK1024 CCD



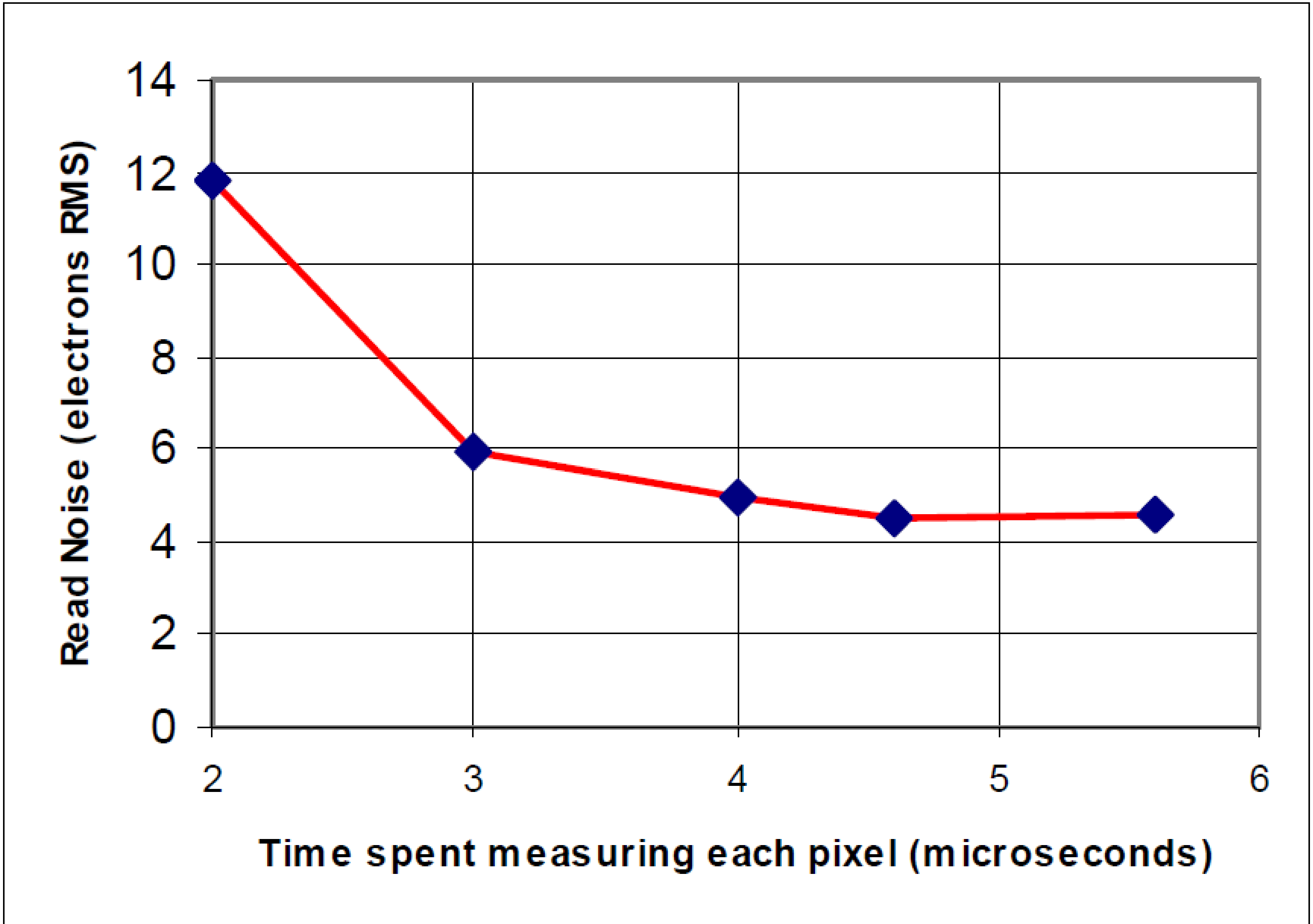

If the object is very faint, perhaps you should get "dark frames" of the same exposure time as the "science frame". In this case, "bias frames" are not needed, as the "dark frame" includes bias counts + accumulated extra counts from the dark current.
Science Frame
Dark Frame
"dark" includes the bias level
Flat Field Image
Bias Image
Science -Dark
Flat -Bias
Science -Dark
Flat-Bias
Output Image

For modern CCDs cooled to low temperatures, the dark current is very low, and therefore we could ignore dark current and only use “bias frames”.



Readout noise

noise and readout speed for an EEV4280 CCD



Noise in a CCD image

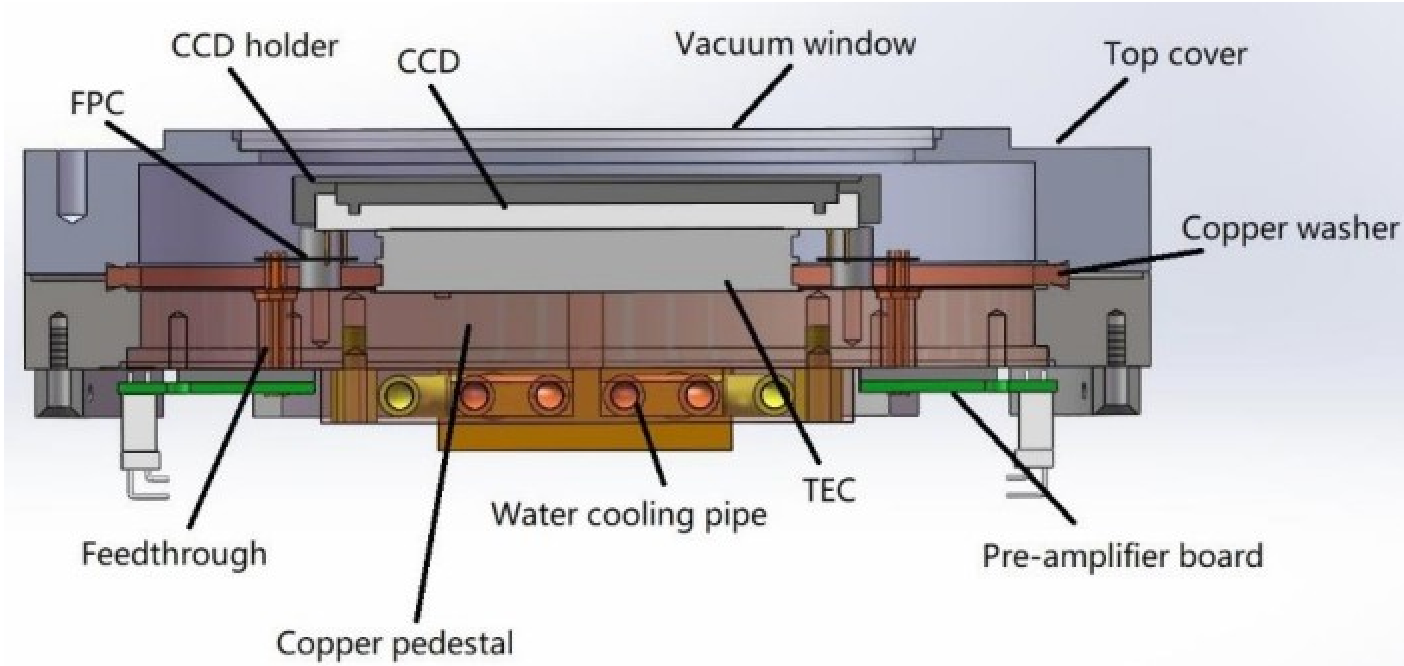
$$\text{NOISE}_{\text{total}} = \sqrt{(\text{READ NOISE})^2 + (\text{PHOTON NOISE})^2 + (\text{DARK CURRENT})^2}$$

Per "frame"

Sqrt(e-)

Can be lowered cooling the detector (CCD: liquid nitrogen or thermoelectric cooling; Infrared detectors: liquid nitrogen or helium)

Resfriamento via liquid nitrogen ($) or Thermoelectric cooling



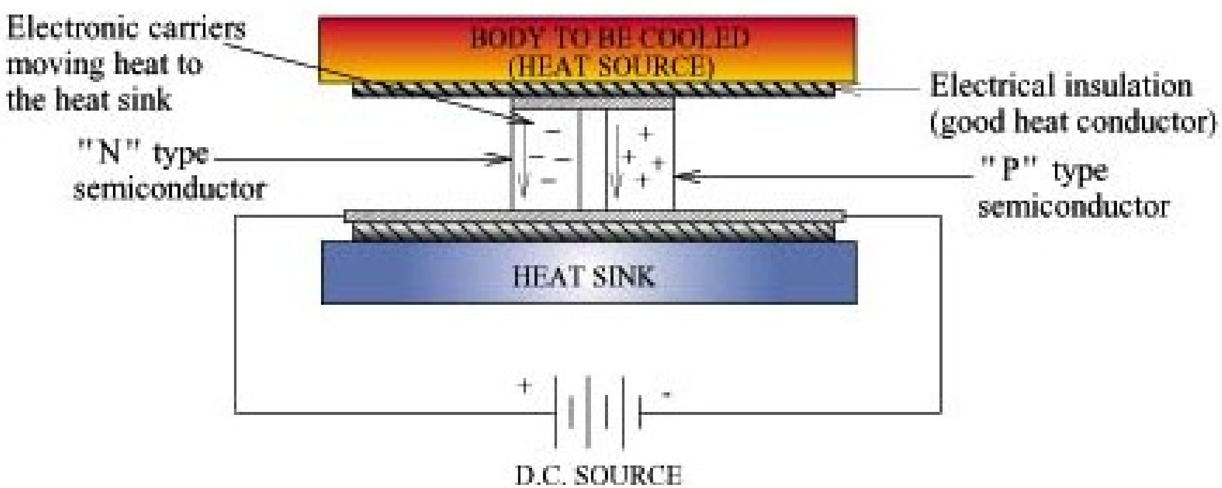


Figure 1. Illustration of a Thermoelectric Module [1].

Linearity

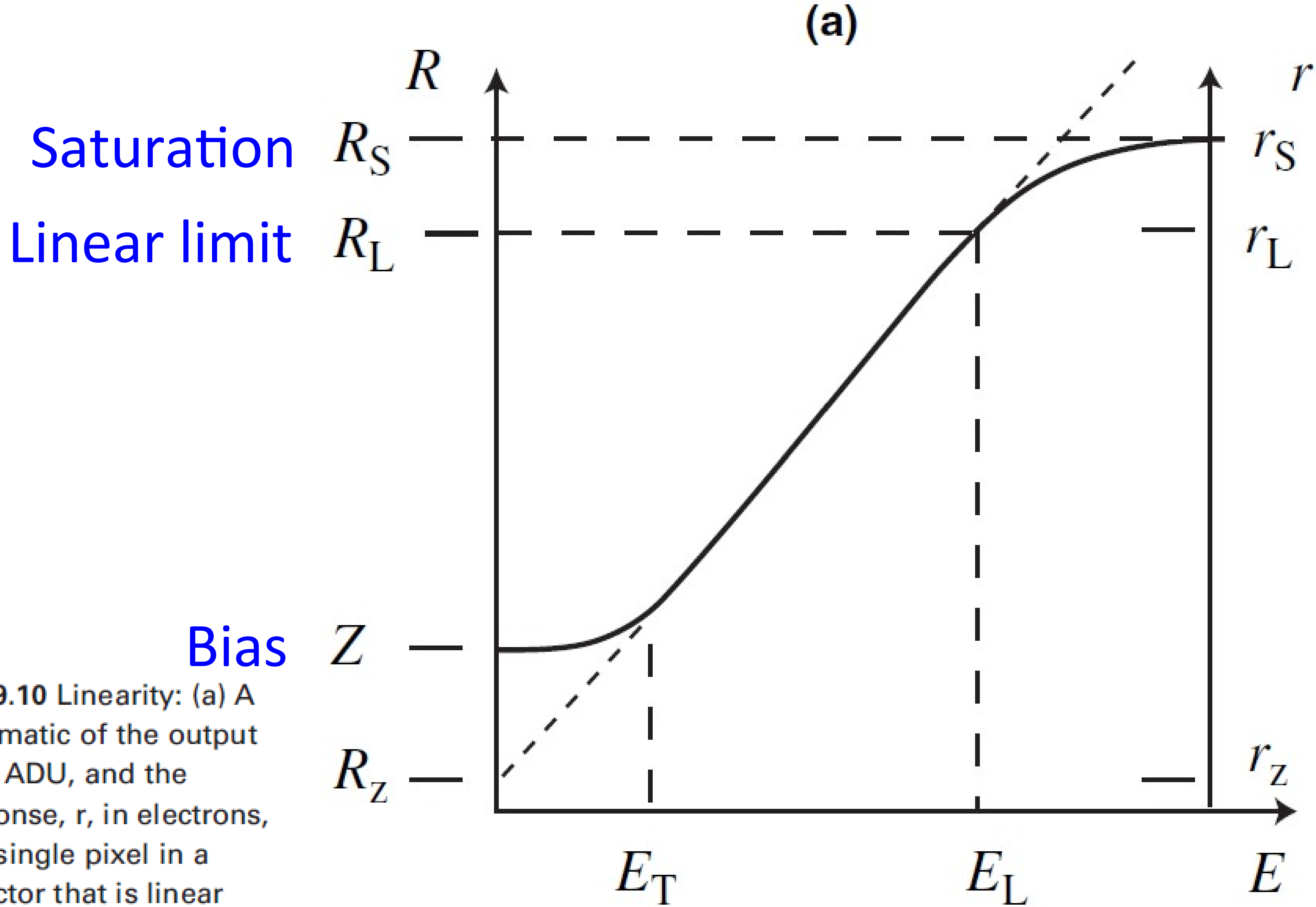


Fig. 9.10 Linearity: (a) A schematic of the output R, in ADU, and the response, r, in electrons, of a single pixel in a detector that is linear over a restricted input range. The sloped

Count vs. e-: GAIN

- Gain is reported in terms of electrons/ADU (analog-to-digital unit)
- Gain = 8 means each "count" = 8 e-
- 8e-/ADU
- In statistics (e.g. photon noise) you must use the number of e- and not the counts (ADU)

CCD IkonL 9867

Resfriamento via Thermoelectric cooling

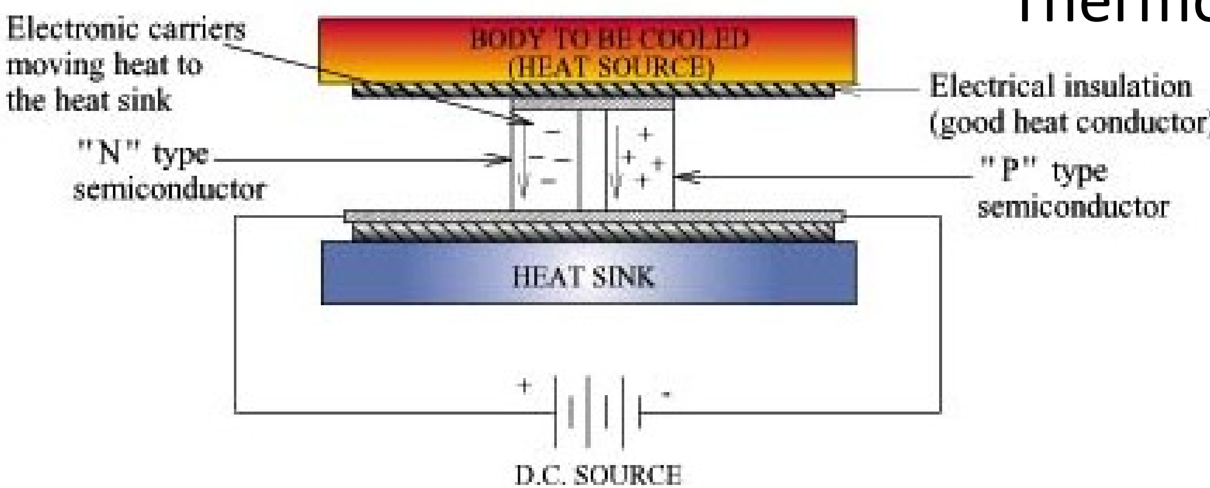


Figure 1. Illustration of a Thermoelectric Module [1].

1,6m
22/5/22

No DS9, display fits header:

GAIN 3.7

RDNOISE 26.6

Saturação = 78041e- / 3.7 = 21092 counts

CCD IKON L 9867

A/D Rate MHz – all 16 bit	Preamp setting	CCD sensitivity e- per A/D count	Single Pixel Noise (e- RMS)	Base Mean Level (ADUs)
5.0	x 1	6.1	56.3	2196
5.0	x 2	3.3	35.0	3340
5.0	x 4	1.8	29.7	4983
3.0	x 1	3.7	26.6	1335 ⟵
3.0	x 2	2.0	16.6	1756
3.0	x 4	1.0	12.2	2094
1.0	x 1	3.5	9.2	930
1.0	x 2	1.9	7.7	909
1.0	x 4	1.0	6.3	839
0.05	x 1	3.5	3.9	873
0.05	x 2	1.9	3.3	852
0.05	x 4	1.0	3.1	813
Saturation Signal per pixel			**78041 electrons**	

Zeiss
22/5/22

No DS9, display fits header:

GAIN 5.2

RDNOISE 24.4

Saturação = 149122e- / 5.2 = 28677 counts

CCD IKON 23777

A/D Rate MHz - all 16 bit	Preamp setting	CCD Sensitivity ♦3 e- per A/D count		Single Pixel Noise electrons rms		Base Mean Level A/D counts	
		High Sensitivity Mode	High Capacity Mode	High Sensitivity Mode	High Capacity Mode	High Sensitivity Mode	High Capacity Mode
5.0	x1	6.9	24.8	38.6	118.4	2263	1135
5.0	x2	3.4	11.1	27.2	65.7	3514	1341
5.0	x4	1.7	6.3	21.4	55.4	4761	1657
3.0	x1	5.2	20.5	24.4	100.5	1032	974 ⇦
3.0	x2	2.7	11.1	15.6	63.7	1597	1459
3.0	x4	1.4	5.7	11.7	46.6	2085	2335
1.0	x1	4.9	20.3	11.6	47.0	970	1271
1.0	x2	2.6	10.5	9.1	34.1	1237	1797
1.0	x4	1.2	5.9	7.3	28.4	1713	2761
0.05	x1	5.0	21.0	5.9	20.8	947	1215
0.05	x2	2.6	11.4	4.9	14.8	1255	1759
0.05	x4	1.2	5.8	4.0	12.5	1822	2760
Saturation Signal per pixel ♦14				149122		electrons	

Poisson distribution (of variable x)

Describes distribution in counting experiments

μ: average rate (e.g., #contagens/s)

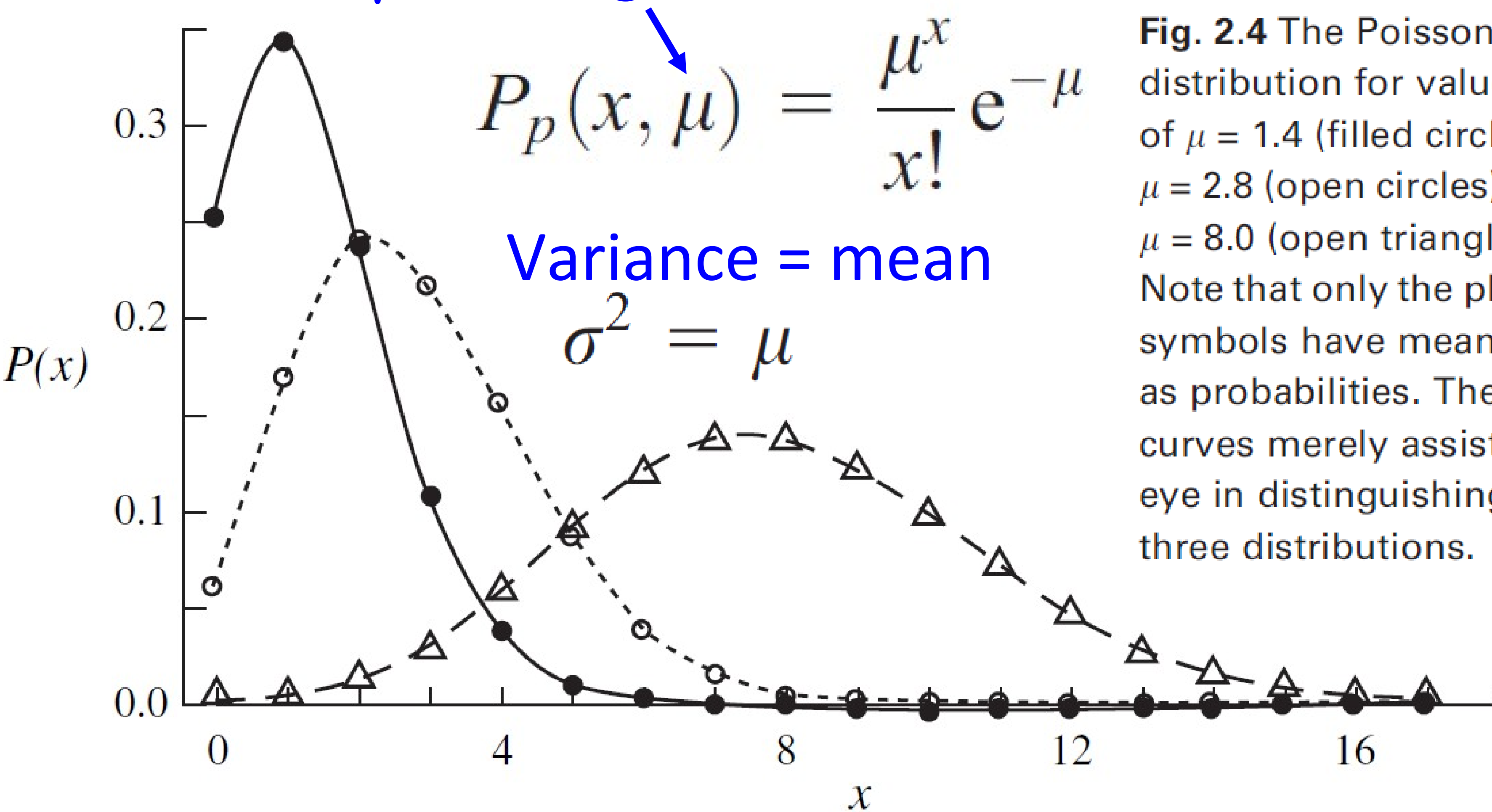


Fig. 2.4 The Poisson distribution for values of $\mu = 1.4$ (filled circles), $\mu = 2.8$ (open circles), and $\mu = 8.0$ (open triangles). Note that only the plotted symbols have meaning as probabilities. The curves merely assist the eye in distinguishing the three distributions.

For example, if you hear average of 2.8 drops of rain/second, probability P(x, 2.8)

Poisson distribution (of variable x)

Describes distribution in counting experiments

μ: average rate (e.g., #contagens/s)

$$P_p(x, \mu) = \frac{\mu^x}{x!} e^{-\mu}$$

N: número de fótons/s

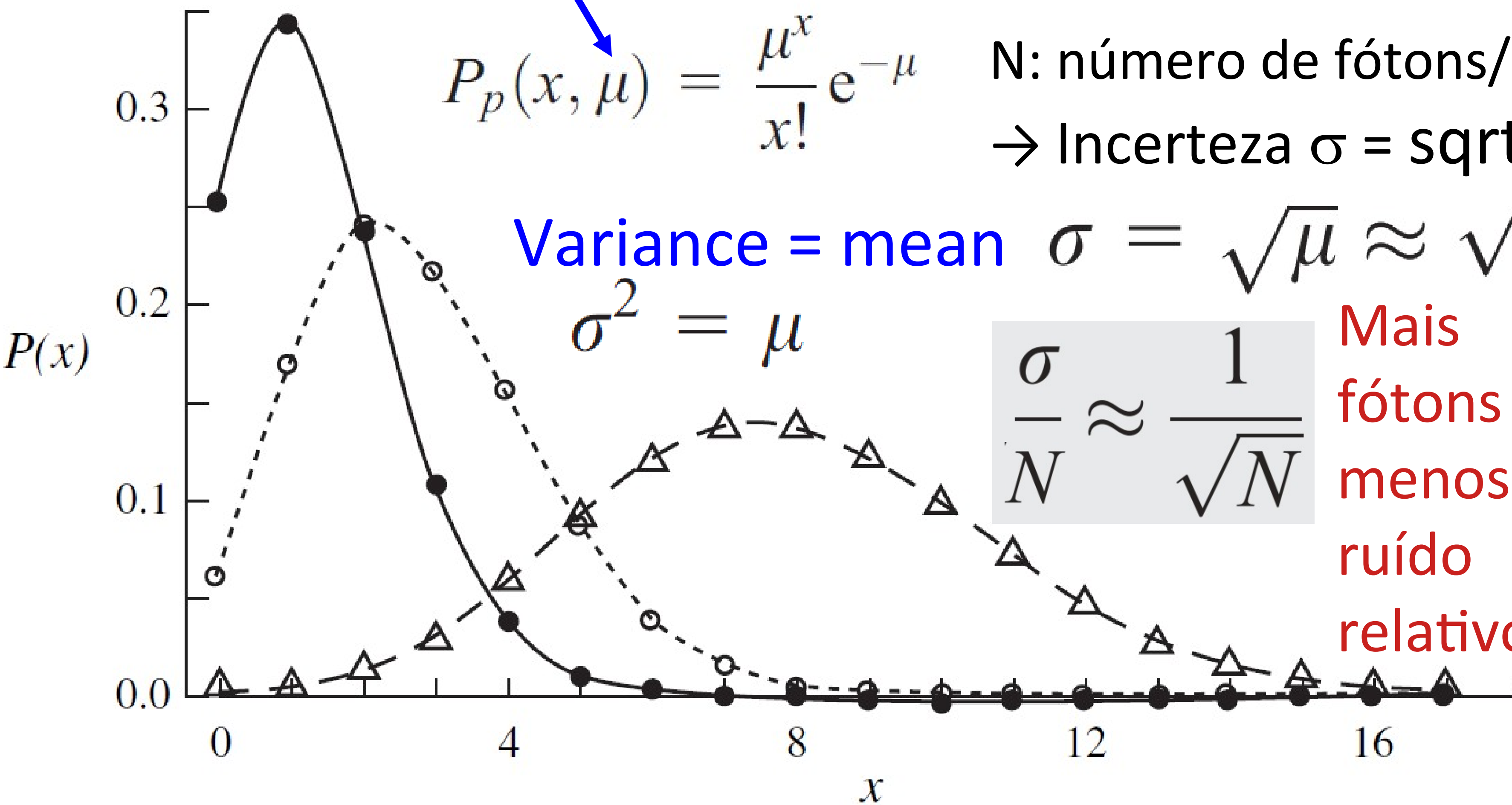
→ Incerteza σ = sqrt(N)

Variance = mean $\sigma = \sqrt{\mu} \approx \sqrt{N}$

$$\sigma^2 = \mu$$

$$\frac{\sigma}{N} \approx \frac{1}{\sqrt{N}}$$

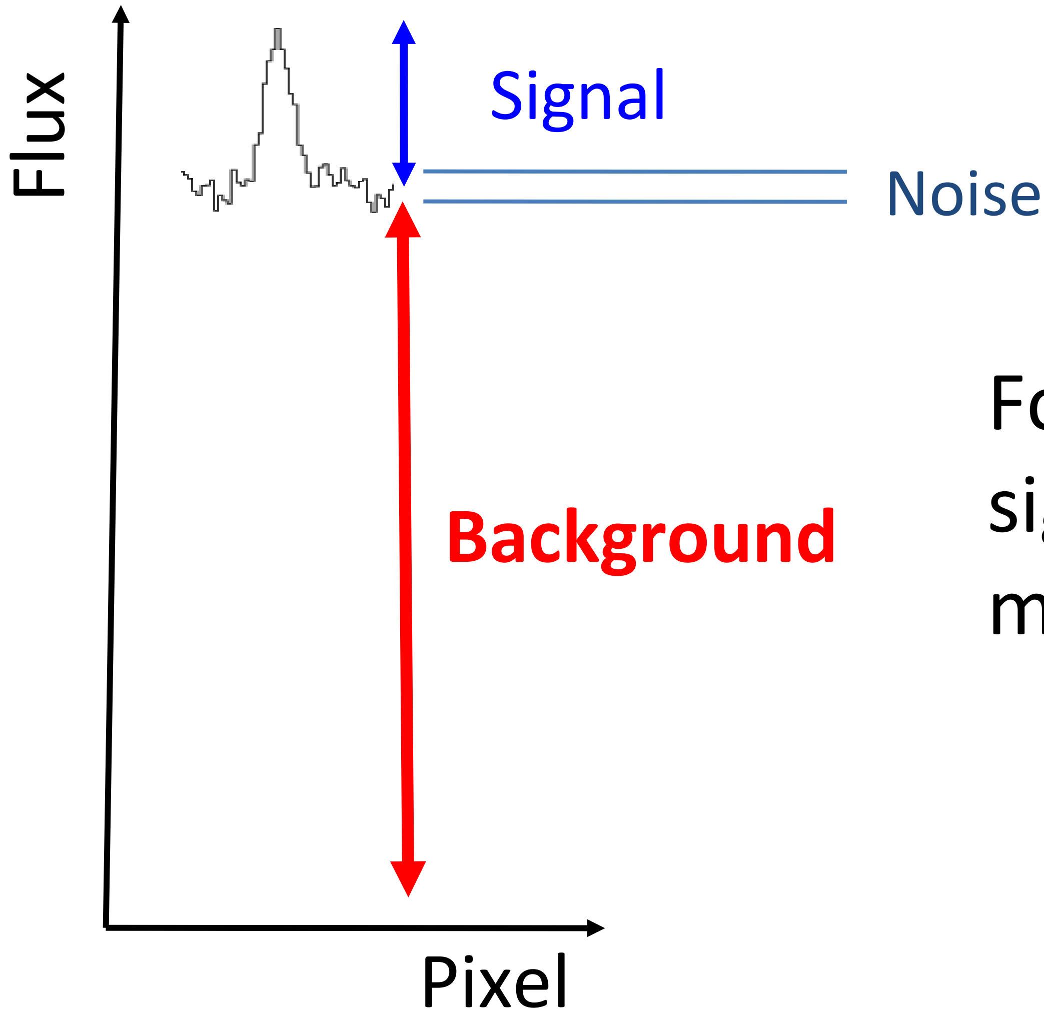
Mais fótons → menos ruído relativo



For example, if you hear average of 2.8 drops of rain/second, probability P(x, 2.8)

Signal, noise & background

Is it possible to detect a signal weaker than the sky background?



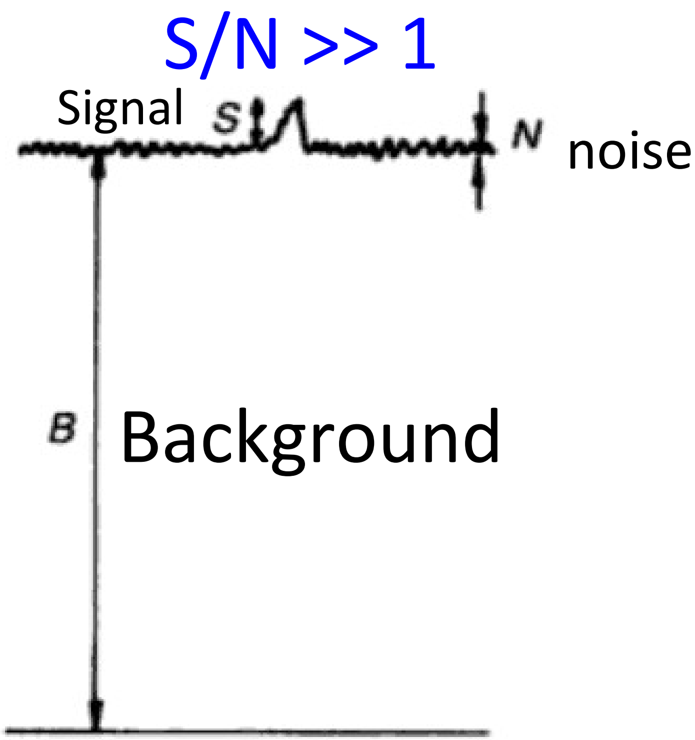
For a detection, the signal >> noise, meaning S/N >> 1

Signal-to-noise ratio (S/N)

S/N = 2: tentative detection

S/N = 3: OK

S/N = 5: firm detection



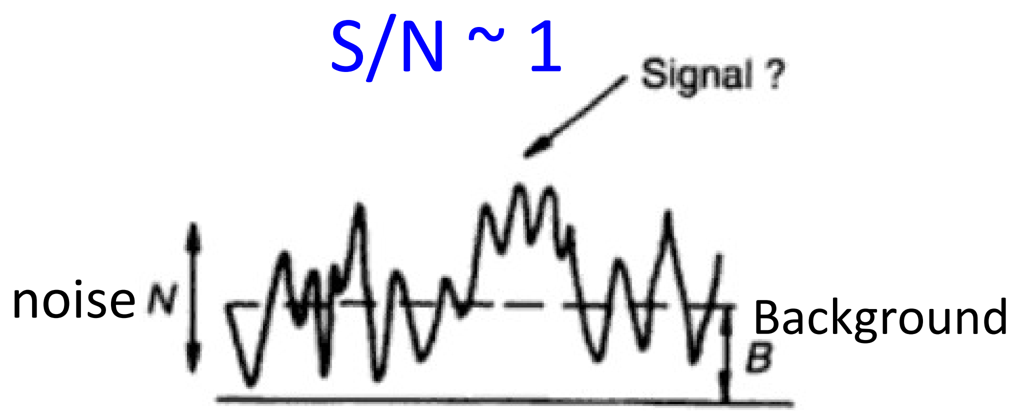
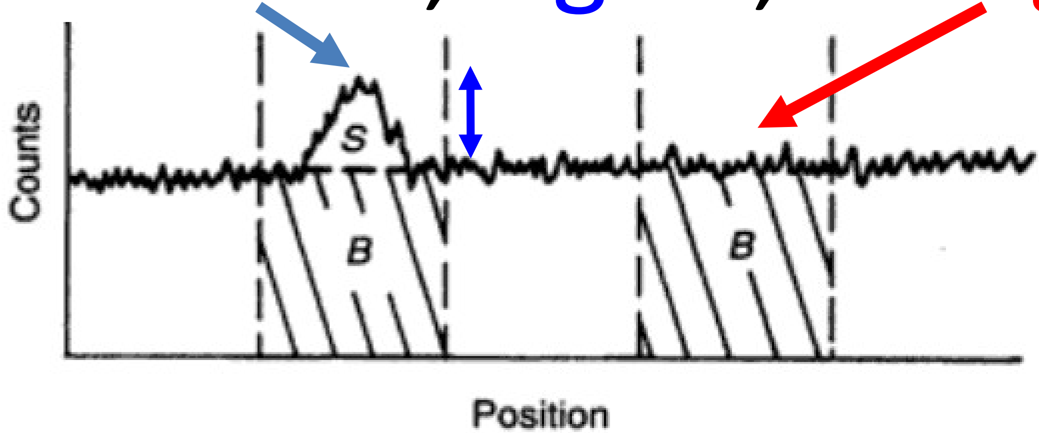


Fig. 3.27. Two extreme examples of noise. In the left-hand diagram, the signal is very weak compared to the background, but is easily detected because the signal-to-noise ratio is large: $S << B$ but $S/N >> 1$. In the right-hand diagram, the signal is comparable in intensity to the background, but its very existence is in doubt because the signal-to-noise ratio is of order one: $S \simeq B$ but $S/N \simeq 1$.

Measurement, signal, background



$$S = M - B$$

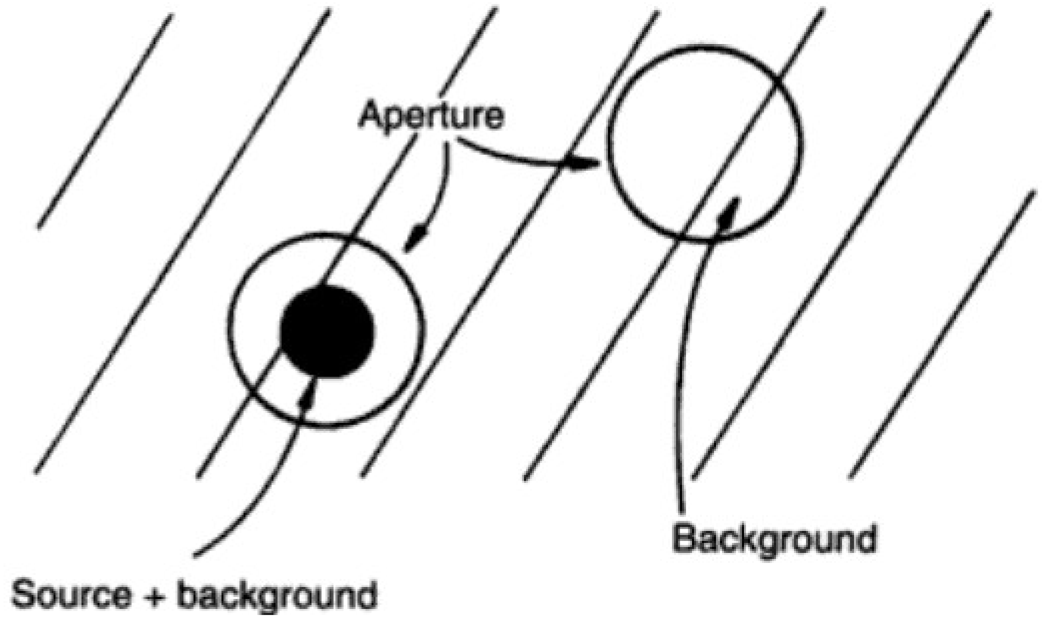


Fig. 3.28. The measured signal always includes the background. The vertical dashed lines in the upper diagram, and the circles in the lower diagram, represent the aperture through which the measurements are made (see text).

Measurement, signal, background, noise

- **$S = M - B$**
- **$\sigma_S^2 = \sigma_M^2 + \sigma_B^2$**

- Neglecting readout noise & dark current:

$S/N = \langle S \rangle/\text{noise} = \langle S \rangle/\text{sqrt}(\sigma_S^2)$

$S/N = (\langle M \rangle - \langle B \rangle)/\text{sqrt}(\sigma_M^2 + \sigma_B^2)$

Measurement, signal, background, noise

- $S = M - B$
- $\sigma_S^2 = \sigma_M^2 + \sigma_B^2$

- Neglecting readout noise & dark current:

$S/N = \langle S \rangle/noise = \langle S \rangle/sqrt(\sigma_S^2)$

$$S/N = (\langle M \rangle - \langle B \rangle)/sqrt(\sigma_M^2 + \sigma_B^2)$$

$$S/N = (\langle M \rangle - \langle B \rangle)/sqrt(M + B)$$

Measurement, signal, background, noise

- $S = M - B$, $\sigma_S^2 = \sigma_M^2 + \sigma_B^2$

S/N = (<M> - <B>)/sqrt(M + B)

If B ~ 0 (e.g., low sky emission):

S/N ~ <M>/sqrt(M)

S/N = sqrt(M)

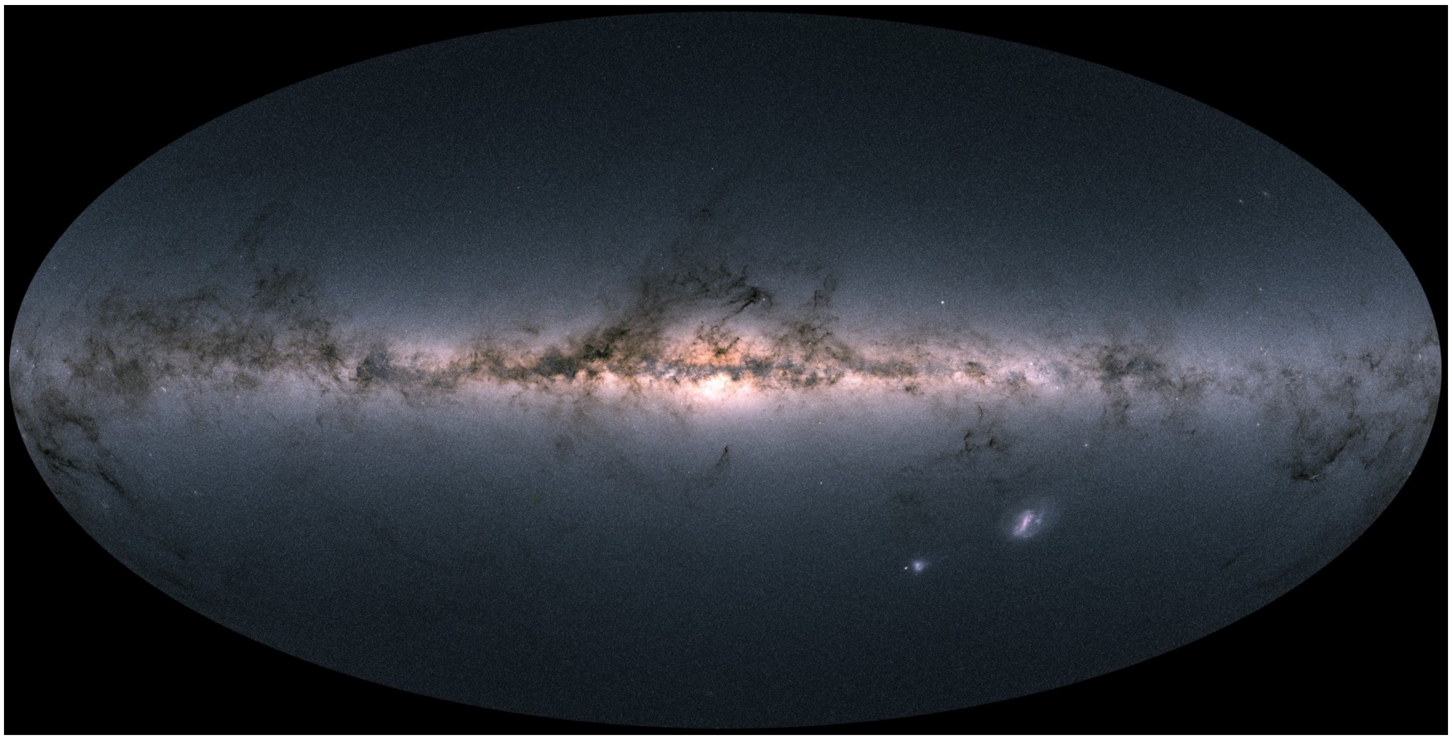
Example, M=10000 e-, → S/N = 100

Slides from previous years

GAIA DR2 party 25/4/2018

GAIA DR2

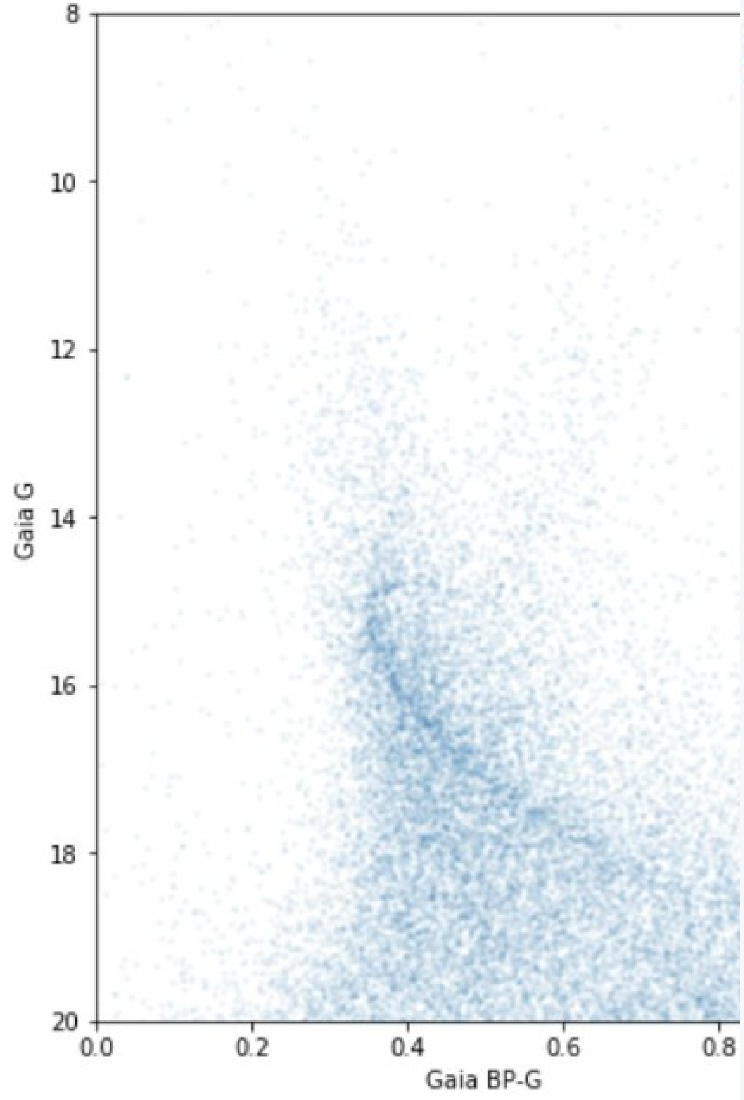
G magnitudes for 1.7 billion sources, colors for 1.4 billion.
Positions, parallaxes, proper motions for 1.3 billion stars.
T_{eff} for 161 million, Radial velocities for 7.2 million stars



Release 25/April/2018. More than 60 papers in 4 weeks!

Natalie Gosnell @Nattie_G_ · 25 de abr

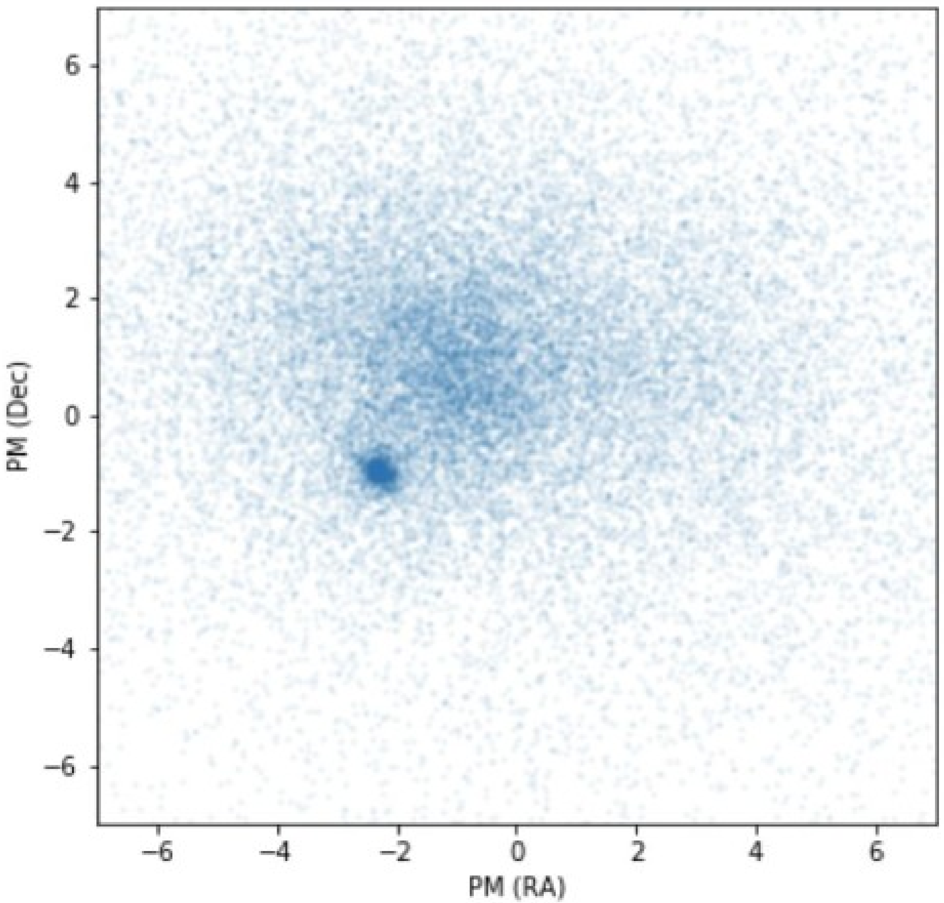
A quick trip into the #GaiaDR2 data, chasing my favorite open cluster, NGC 188. Here are all ~37k sources within 1 deg of NGC 188. The main sequence is visible, but can we do better?



Natalie Gosnell @Nattie_G_ · 25 de abr

Let's look at the proper motions! The overdensity around -2.25 RA, -1.0 Dec is the cluster! What happens if we make a quick cut around that overdensity? **drum roll**

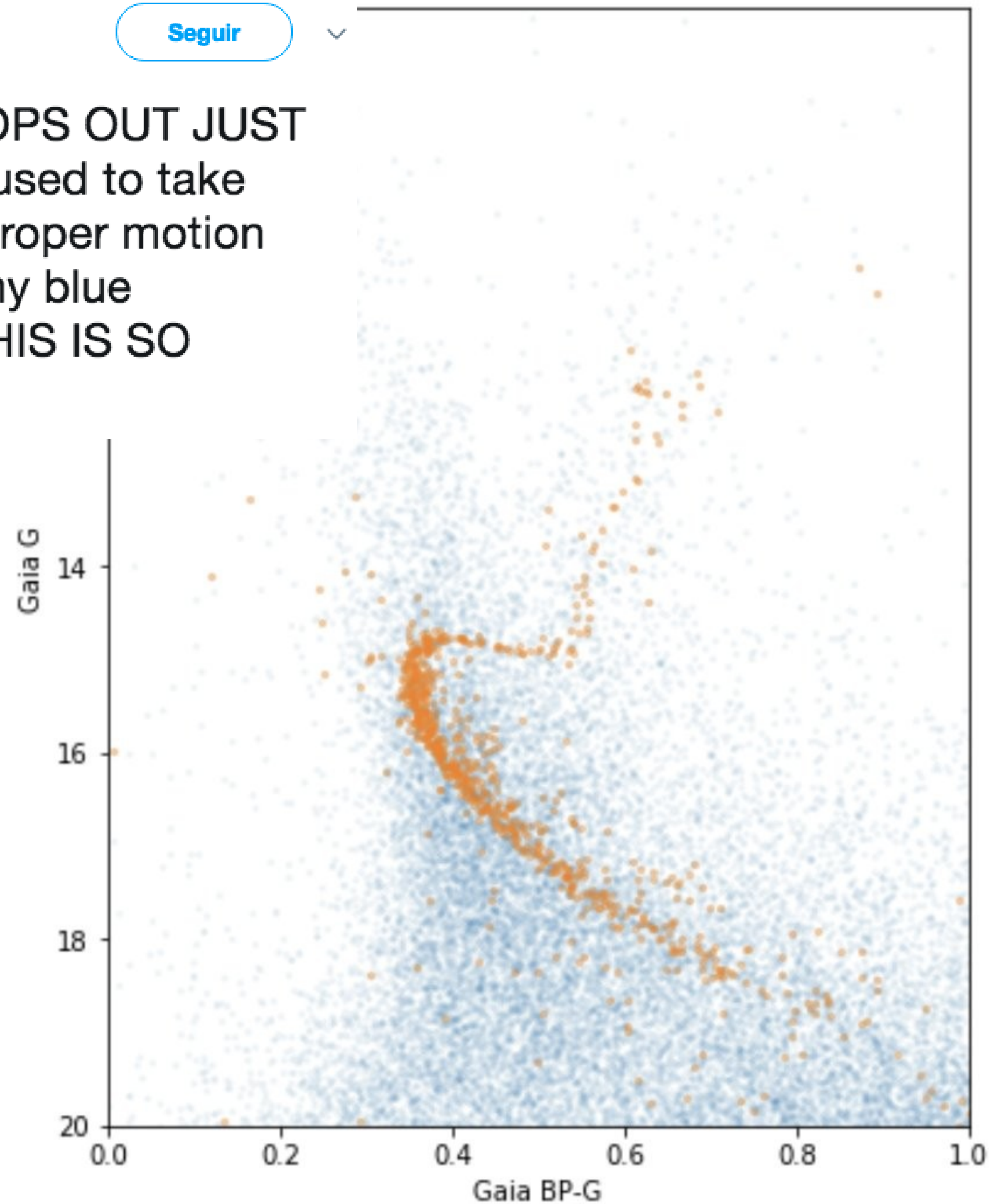
Traduzir Tweet



Natalie Gosnell
@Nattie_G_

Seguir

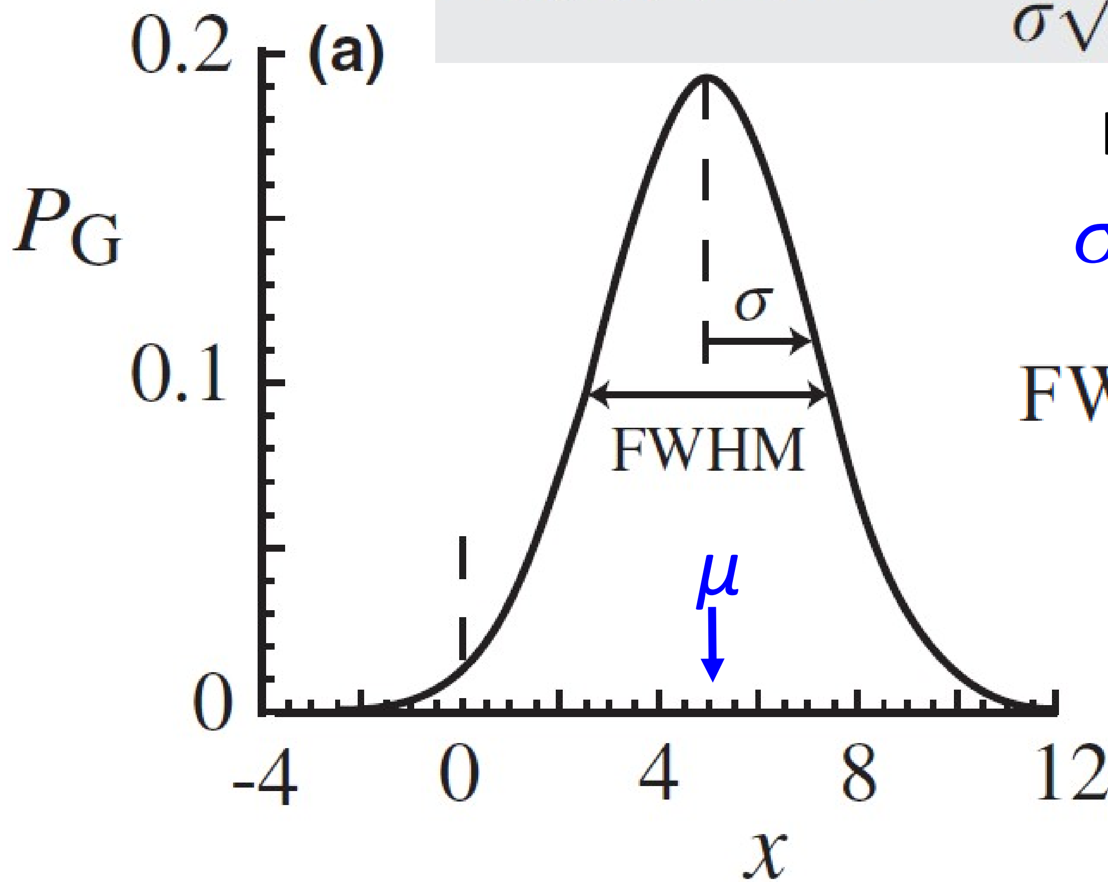
THE CLUSTER CMD POPS OUT JUST LIKE THAT! Folks. This used to take YEARS of painstaking proper motion analysis. YEARS! And my blue stragglers are there!!! THIS IS SO COOL!!! ✨ #GaiaDR2



Gaussian (or normal) distribution

Seems to describe the distribution of very large number of different experiments

$$P_G(x,\mu,\sigma)\mathrm{d}x = \frac{\mathrm{d}x}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]$$



Is a continuous distribution

σ is independent of μ

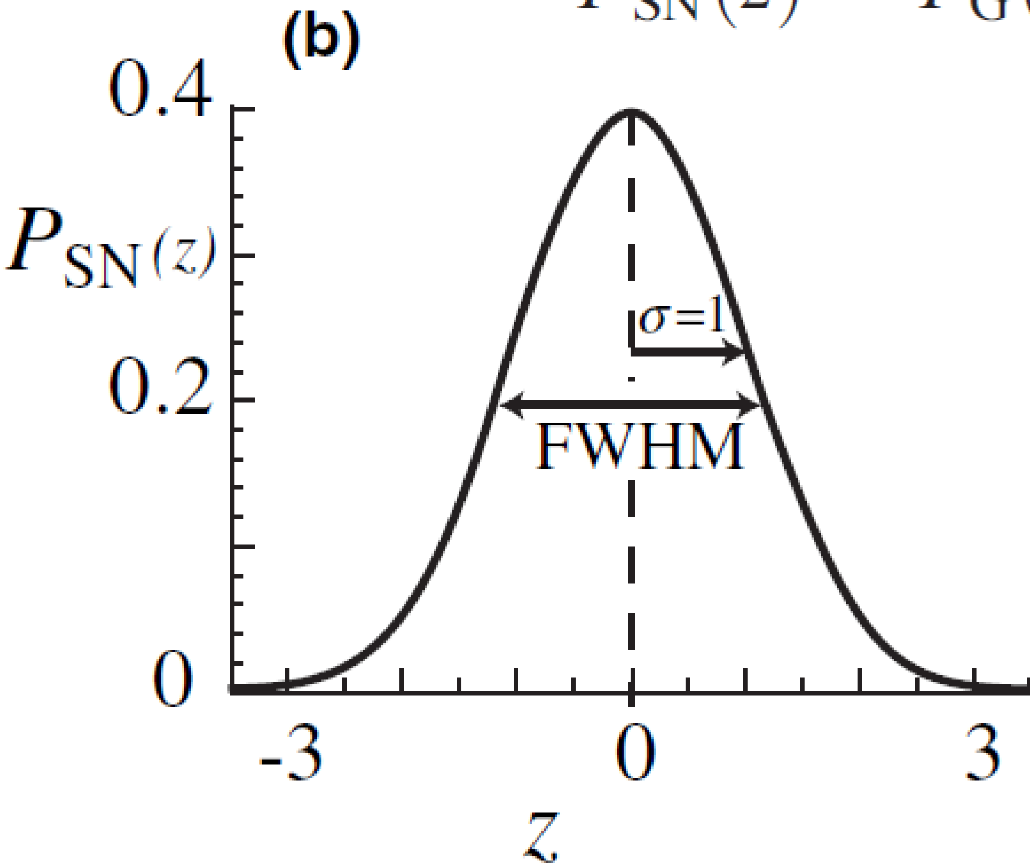
$$\mathrm{FWHM}_{\mathrm{Gaussian}} = 2.354\sigma$$

Fig. 2.5 (a) A Gaussian distribution with a mean of 5 and a standard deviation of 2.1. The curve

Standard normal distribution

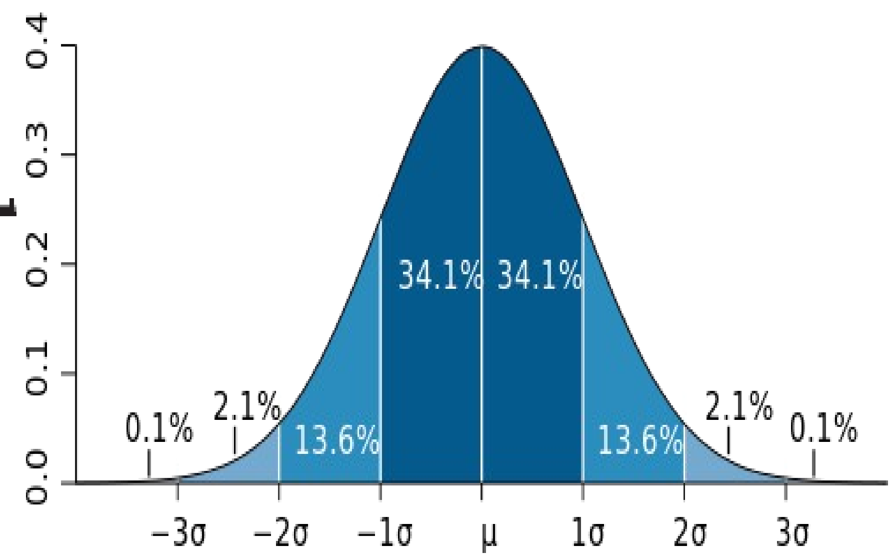
$$P_{SN}(z) = P_G(z, 0, 1) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{z^2}{2}\right]$$

$x \ \mu \ \sigma$



$$z = \frac{x - \mu}{\sigma}$$

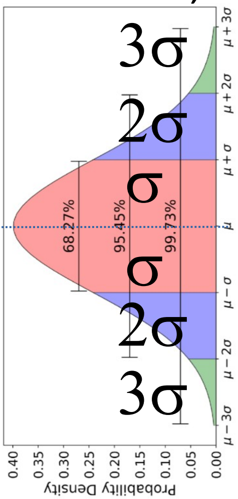
$$dz = \sigma^{-1} dx$$

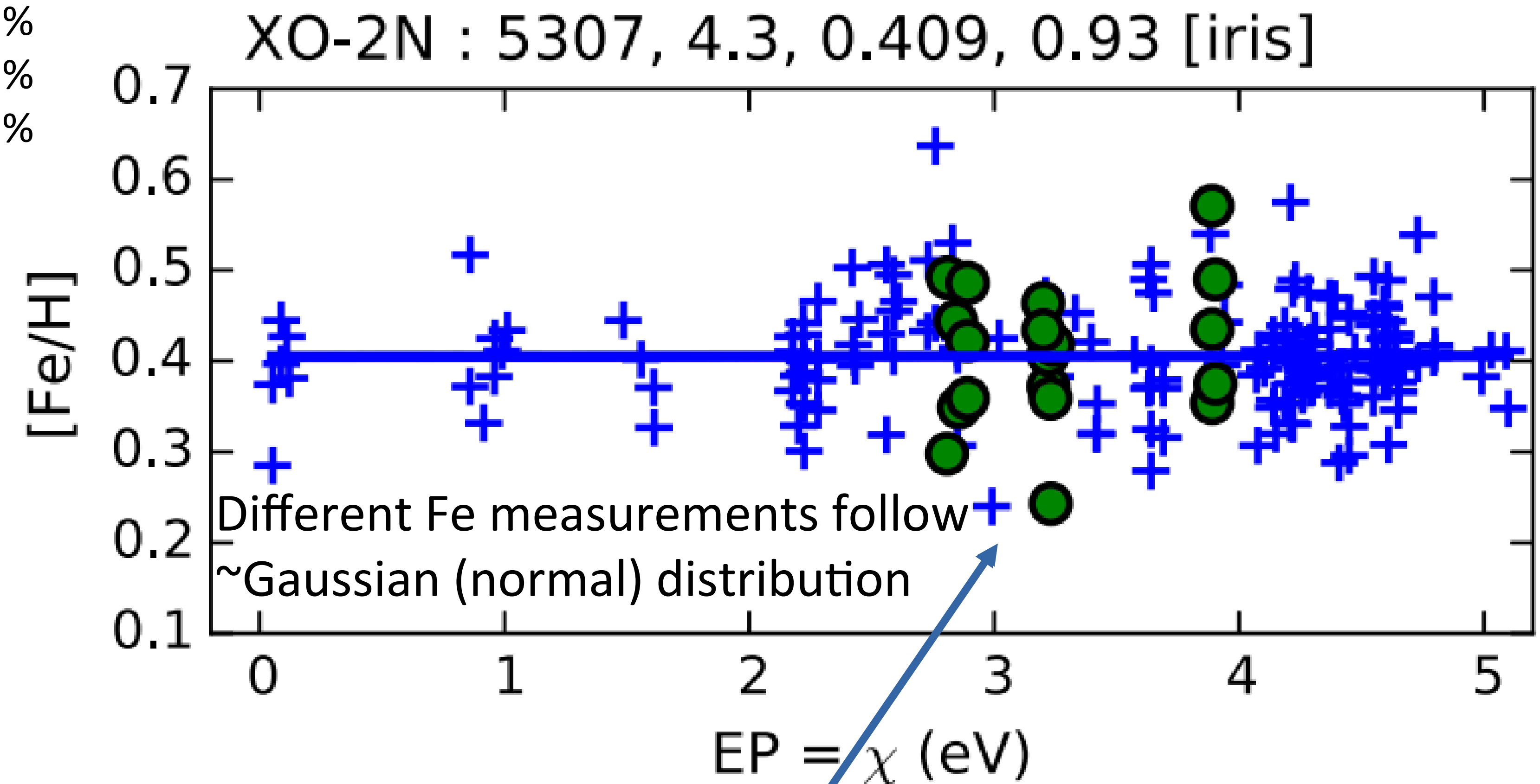


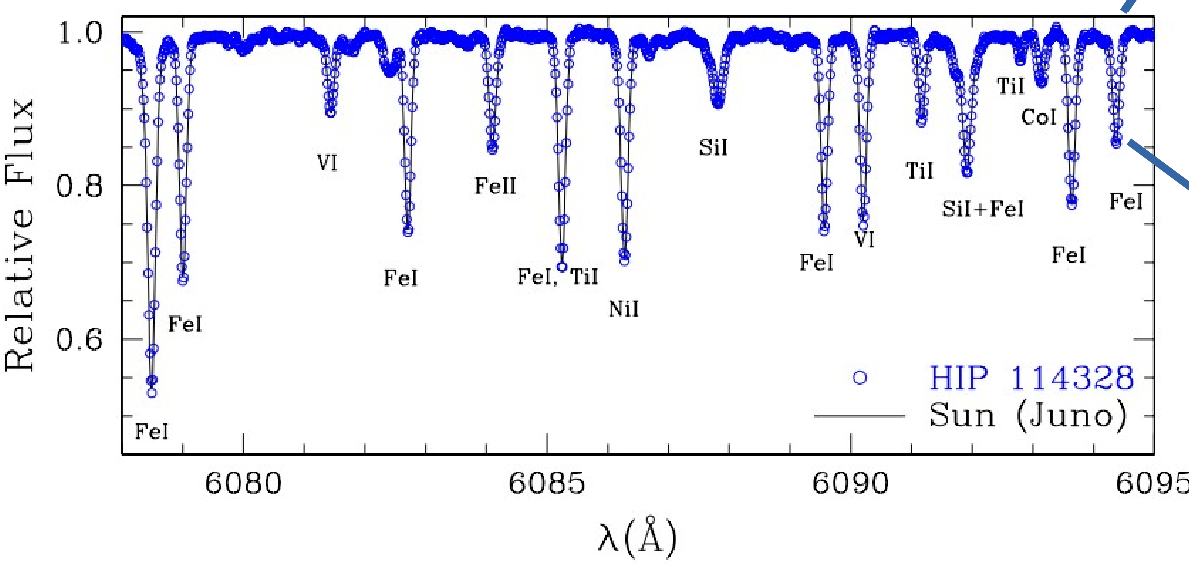
± 1σ: 68,27%

± 2σ: 95,45%

± 3σ: 99,73%







Each Fe measurement has an an error (Poisson distribution)